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HEAT STERILIZABLE IMPACT RESISTANT CELL DEVELOPMENT

FOR THE

JET PROPULSION LABORATORY

CONTRACT 951296

FINAL REPORT

ON

CELL DEVELOPMENT

COVERING PERIOD

OCTOBER 1, 1967 TO SEPTEMBER 1, 1971

ESB INCORPORATED
EXIDE MISSILE AND ELECTRONICS DIVISION
RALEIGH, NORTH CAROLINA

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ABSTRACT, CONCLUSIONS, AND RECOMMENDATIONS

I. DEVELOPMENT OF 25 AH HIGH SHOCK CELLS

A. Engineering model 25 AH cells survived 4,000 "g" peak shock loads in all axes except terminals-forward.

B. Prototype 25 AH cells designed, fabricated, and electrically tested but not shock tested had the following characteristics:

1. Positive plates with .037 inch Zirconium struts to prevent buckling in the terminals-forward axis.

2. Negative plates with teflonated active zinc oxide contained in pockets chemically etched from massive Ag sheet. The active material accounts for 65 to 70% of the finished plate volume.

3. Hydrogen evolution from the negative plates during formation charge was increased by the massive Ag grid. Acceptable control was achieved by plating mercury on the grid surface and by a low rate formation charge.

4. Design limitations to meet 4,000 "g" shock:

   (a) Plate width - 0.75 to 1.25 inches.
   (b) Plate height-to-cell length ratio - 1.0 to 1.5.
   (c) Effective structural core thickness in plates - .010 to .020 inches.

5. Cycle life achieved - 72 to 121 with 10 hr. charge/2 hr. load to 50% depth after heat sterilization for 72 hr. at 135°C.

6. Energy densities - 21.5 WH/lb. and 1.6 WH/in^3 of cell at C/2 rate.

II. DEVELOPMENT OF 5 AH HIGH SHOCK CELLS

A. Five ampere-hour cells (ESB Model 361) were developed to withstand 4,000 "g" shock from 120 feet/second in all axis. Prototypes were submitted for JPL tests and passed the 4,000 "g" test terminals trailing. At the C rate of discharge, energy density was 10.6 WH/lb. and 0.9 WH/in^3.

B. Design factors for the 5 AH cell were similar to the 25 AH cell - a 1/5 scale model.

C. Positive plates contained zirconium cores and struts. Titanium and silver plated Inconel 600 were also tested. Titanium evolved hydrogen during heat sterilization. Silver plated Inconel 600, while sterilizable in the cell electrolyte, gave poor electrochemical performance unexpectedly.

D. Negative plates contained chemically etched silver grids with pockets for supporting the active material. The teflonated zinc oxide mixes were sintered at 325°C and then pasted into the grid to prevent a 70% loss in grid tensile strength caused by annealing the hardened silver grid if heated at 325°C for 1 hour.

E. Capacity tests in non-shock 10 AH development cells revealed capacity losses from material interactions during or following heat sterilization for 120 hours at 135°C.

- RNF-100 heat shrinkable tubing used for plate lead insulation markedly increased hydrogen evolution from negative plates on formation charge and decreased capacity 41% to 5.9 AH.
- With RNF-100 insulation and E-1488 non-woven polypropylene retainers on negative plates, capacity was further reduced to 5.1 AH.
- Without RNF-100 insulation or polypropylene retainers, zirconium cores in positives reduced capacity 17% over and above the 17% loss equivalent to the active material displaced.

F. An early model five ampere-hour cell (ESB Model 344), using only silver for plate support structure survived shocks up to 2,400 "g" in all axis. Shocks in range 2,400 to 3,000 "g" gave capacity losses up to 30% re-storeable on subsequent cycles.

G. JPL drop tested batteries using 12 Model 344 cells in the CSAD capsule with acceptable mission performance after shocks in the range 1300 to 2400 "g".

III. DEVELOPMENT OF 70 AH CELLS AND BATTERY

A. A 70 AH cell was developed for an 18-cell 2000 WHr. battery. After heat sterilization for 72 hours at 135°C mean energy density was 53 WH/lb. and 3.7 WH/in^3 when discharged at the C/4 rate to 1.25 volts.

B. Prototype cells delivered 16 cycles in a wet life of 16 months and met or exceeded all performance goals except consecutive mission storage and active life.

C. Twenty-seven reliability cells were manufactured, sterilized, and tested for 30 days on float at 1.87 volts/cell, on discharged stand, and on charged stand. Cells were shipped to JPL at task termination.

D. Three cells, cycled five 100% depth cycles, were let-down discharged to a stable open-circuit voltage of 10-20 millivolts and then sterilized 120 hours at 135°C. On the next cycle a capacity loss of 30% was observed.

IV. DEVELOPMENT OF 25 AH LOW IMPACT INTERMEDIATE CYCLE LIFE CELL

A. A 25 AH cell was developed to provide 90 cycles of 50% depth of discharge after heat sterilization, launch, interplanetary travel, and a 250 "g" soft landing. This cell design (ESB Model 379) has delivered up to 168 cycles of 10-hour charge/2 hour discharge in 9.5 months wet life.

B. At the C/3 rate of discharge, delivered energy densities were 44 WH/lb. and 2.68 WH/in^3 of sealed cell after sterilization 72 hours at 135°C.

C. Failure occurred after an accumulated output of 77 X rated capacity (1920 AH), and mode of failure was silver and zinc penetration through a separator system of 1L Pellon 2530 W and 7L SWRI-GX membrane.

D. An evaluation of the effect on initial cycle output capacity of 72 hours heat sterilization at 135°C, a pretest, and an epoxy-plate-lock yielded the responses:

- Heat sterilization - 5.4%
- Pretest - 1.9%
- Epoxy platelock -14.8%

E. The 6-cycle pretest decreased accumulated capacity to failure by negative erosion and/or silver penetration 21% averaged over four similar cell designs.

F. It is recommended that the value of a pretest prior to sterilization be critically examined. Correlation with ultimate performance should be high if the pretest sacrifices a portion of battery life.

V. DEVELOPMENT OF HIGH CYCLE LIFE LOW IMPACT CELLS

A. A contract goal was a 20 AH cell capable of 400 cycles at 50% depth of discharge one cycle per day, and a wet life to include sterilization of 120 hours at 135°C, charge, lift-off environments, 9-month interplanetary travel, and a soft landing shock of 200 "g".

B. The optimum design 20 AH cell achieved 241 cycles on a 20 2/3 hour charge, 3 1/3 hour discharge after 72 hours sterilization at 135°C in nitrogen. At the 8.0 ampere discharge rate the delivered energy density was 30 WH/lb. and 1.8 WH/in^3 of cell.

C. Failure mode of the final design was negative plate erosion in spite of the following design features:

- ZnO/Ag ratio by weight of 1.67.
- Negative plate edges extended 0.1 inch beyond positives.
- Separator system of 1L Pellon 2140 and 8L SWRI-GX wrapped on positives.
- Electrolyte 43% KOH containing 114 g ZnO/liter.
- Dual negative 3/0 grid 0.48 g/in^2 silver.
- Sintered teflonated negative active material.

D. Rate of capacity decay was 0.3% of initial C/3 rate capacity per cycle on the 20 2/3 hour charge/3 1/3 hour discharge and 1.0% per cycle on the 10 hour charge/14 hour discharge regime.

E. Electrolyte mossing was observed during the 11-month cycling test at the cell terminal to cover seals at a frequency of 7 in 60. Electrolyte leakage was however not a mode of failure.

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I. DEVELOPMENT OF 25 AH HIGH SHOCK CELLS

A. Objectives and Previous Accomplishments. - Original and project design goals included development and test of non-magnetic 25-50 AH sealed Ag-ZnO cells capable of wet heat sterilization 120 hours at 135°C, charge, pre-flight tests, launch, and 8 months float or charged stand during interplanetary travel. After planet entry the cells would be required to survive in the spacecraft a hard landing shock of 2800 ±200 g from 113 ±2 feet per second in any axis and then cycle 4 deep cycles at 100% of rated capacity.

After cell qualification an 18 cell 25 AH battery would be developed to deliver 600 WH energy at 300W at energy densities equal to or greater than 25 WH/lb of battery.

Previous tests[(1)] of 25-50 AH cells at shocks with measured peaks in range of 6,000 to 23,000 g demonstrated:

- Plate active materials are not capable of supporting own weight during impact in ± y and ± x (height and width) axis.
- Plates must be reinforced with central cores with high tensile strength and stiffness factors.
- Thick wall PPO 531-801 cell jars can be sealed by epoxy with a massive cover assembly designed to lock in place all plate core structures. Failure mode will be peel at epoxy to PPO interface.
- Stress analyses on cell components and assembly can predict failure modes provided material strengths after heat sterilization are known and assumptions are valid for structural model.

B. Plate Central Core Structures. -

1. Metals. - Metals offer the advantages of high strength and electrical conductivity when used as plate core structures. An evaluation of the metals offering the possibility of heat sterilization in 45% KOH, high strength per unit weight, low resistivity, and low magnetic susceptibility produced the following candidates:

Characteristic	Pure Silver	Titanium	Zirconium	Inconel 600
Tensile Strength, Annealed, psi	27K	35K	65K	94K
Density, g/cc	10.5	4.5	6.5	8.5
Magnetic Susceptibility	-0.2×10^{-6}	3.2×10^{-6}	1.3×10^{-6}	400×10^{-6}
Resistivity, micro ohm-cm	1.6	50	40	98
Tensile Strength per Unit Density, Annealed, psi x 10^3	71	210	279	395

Of these metals titanium was eliminated because of chemical interraction with 45% KOH solution during heat sterilization at 135°C. Silver was considered a safe control not desirable because of high density, high cost, and low tensile strength after 120 hours at 135°C (22,000 psi). Inconel 600 was believed to be a desirable candidate for core structures although silver plating was required to eliminate interaction with the charged positive AgO. Zirconium eventually proved to be the best metal available for plate structure.

2. Composites. - A desirable plate core structure should have the chemical properties of silver and the physical properties of Inconel. General Technologies Corporation, Reston, Virginia produced for ESB some 2-in. X 4-in. panels of silver and boron filaments.

The silver-boron compoeite structures have the advantage of the high strength of boron filaments coupled with the inertness of the exposed silver metal in the KOH environment. GTL succeeded in adapting silver to their processes for making the high strength composites. When ESB attempted to fabricate plates using the composite panels as the backbone material, several major problems arose. Silver grid required to hold the active materials could not be spotwelded to the composite structure. Also, in the initial samples the boron filaments were exposed around the periphery of the panels which may have created electrochemical problems in the sterilized cells. However, the major objective to the silver-boron composites was the lower than expected value of flexure modules ($12\text{-}19 \times 10^6$ psi) which is less than that for Inconel and no greater than the flexure modules of zirconium. The composite material was therefore not stronger in bending than some of the common metals. Since further development of the silver-boron material would have been both costly and time consuming, its use was deferred at that time in favor of either Inconel or zirconium.

C. 3/4 Framed Electrode Cell Design. - One means for immobilizing cell plates is to cement plate edges to the jar wall along the bottom and vertical sides of each plate. Based on this design hypothesis, a 3 plate (2 half positives, 1 negative) cell was fabricated as follows:

Negative Plate Assembly:

- Inconel 600 sheet 10 mil thick silver plated core.
- PPO 531-801 frames cemented along bottom and vertical edges both sides.
- Ag expanded metal spotwelded to Inconel then flush pasted with negative active material both sides.
- 5 layers SWRI-GX membrane cemented to frame both sides.
- Redundant Inconel 600 and Ag sheet plate tabs.

Positive Half Plate Assembly:

- Inconel 600 sheet 10 mil thick silver plated core.
- PPO 531-801 frames cemented along bottom and vertical edges.
- Silver plate active material with embedded grid spot-welded to Inconel within frame.
- Redundant Inconel 600 and Ag sheet plate tabs.

Cell Assembly:

- Positive half electrode frames cemented on each side of negative electrode.
- 3-plate assembly cemented with shims into PPO 531-801 jar.
- Plate tabs connected to terminals and potted into PPO jar cover and cemented onto jar.

Activation and Seal:

- Activated under vacuum to 42 gms, 43% KOH solution.
- Cell sealed with epoxy coated threaded plug.

During heat sterilization for 120 hours at 135°C in nitrogen, a water loss of 3 grams was observed but no electrolyte leakage. When placed on charge, charge current was erratic and the voltage rose to 2.10 volts in one hour. The cell was opened, reactivated under vacuum, adjusted to level, and sealed. Charge again terminated prematurely after 4 hours. No further charge acceptance was possible. The cell open circuit voltage was not stable. Dissection confirmed plate to terminal connections were correct and separator deeply blackened. Positives were partly charged and evenly over entire surface.

Structurally the cell assembly was attractive because plates are supported in each axis in compression and tension. Fabrication problems were acute and the reliability of the epoxy seal around the plate edges was very questionable. Any failure of this seal could result in a cell short. For these reasons the 3/4 frame design was considered not feasible and dropped from further consideration.

D. Changes in Specification Requirements of High Impact 25 AH Cell. -

All early work on high impact, heat sterilizable cells was performed with JPL Specification GMP-50437-DSN-C as the basis of the design. However, a new specification - JPL Engineering Memorandum 342-68 - was later added for the 25 AH cell which incorporated several major changes to the battery including:

- Reduction in the number of cells from 19 to 12.
- Cycle life of ninety 50% depth cycles after impact compared to only four full cycles in the original specification.
- Impact of 4000 "g" at a landing velocity of 120 feet per second.

The requirement for ESB to deliver multi-cell 25 AH batteries was later deleted; however, development continued on the cells required for these batteries with ESB to deliver only qualified cells. The major design objectives per JPL Engineering Memorandum 342-68 are listed in Table I.

E. Original Design Considerations for 25 AH Narrow Plate Design. -

Normally, the approach for increasing cell capacity of 5 AH cells, which have high impact capability, to 25 AH would be to increase plate size and thickness. However, this would lead to severe problems at 4000 "g" shocks. A second approach would be to maintain the same plate size and stack up a sufficient number of plates for the required capacity. This would lead to severe plate compression of negative material, thus, reducing cycling efficiencies. The ESB narrow plate design has the plates supported in slots in the case wall and a limited plate width to prevent excessive bending deflection out of the slot. An ESB compromise was to have one plate in a slot which supports both itself and the adjacent plate in the separator U-fold. Analyses were performed to determine optimum values of the pertinent structural parameters.

F. Plate Width and Core Thickness. - Stress analyses were performed to determine optimum plate width and core thickness based on the assumptions:

- 3000 "g" shock perpendicular to plane of plates.
- Positive plates contain high strength metal cores and are supported individually in slots. Inconel 600 and zirconium were both considered as support material for positive plate cores.
- Negative plates are stiffened with silver sheet and are supported by adjacent positives.
- Positive active material weight is equal to negative active material weight.

Figure 1 gives the boundaries for core thickness and plate width fixed by either failure analyses or arbitrary limits imposed by JPL cell energy density requirements. Plate width is limited to 0.75-1.25 inches, and the shock supporting core thickness, to 10-20 mils. Earlier tests on AgO plates indicated active material began to shed at .12 inch per inch deflection, therefore, the maximum allowable design deflection was limited to 0.10 inch per inch of span.

G. Optimum Core Thickness in Edgewise Shock. - For the case of shock edgewise and parallel to the plane of the plates, column buckling strength is the critical design factor. Figure 2 gives buckling limits and Euler failure stress for Inconel, zirconium, and silver cores of various thicknesses. Inconel and zirconium at thickness of 15 mil and 17 mil, respectively, have over twice the buckling strength required to withstand the column stress. Ten mil silver sheet can withstand the stress only when supported on either side by the stiffened positives.

H. Preliminary Cell Pack Design, Wrapped Negatives. - The initial electrochemical design parameters were calculated on the assumption of wrapped negative plates with the positives extending into slots in the jar walls. The plate height and cell pack length (or number of plates per cell) were calculated to give:

- Sufficient active plate area to meet voltage requirements under the specification load.

- Plate active material thicknesses to meet load voltages and output energy per unit weight of cell.

Table II lists the detailed design factors. Figure 3 gives the computed cell pack design parameters as a function of the number of negative plates n and ratio of plate height to cell pack, length β . For a plate area of 100 in^2 which is adequate for the required discharge loads, a specific energy density of 20 WH/lb minimum may be obtained in the range of β from 1.0-1.5 and n of 16-20 mils. The β range of 1.0-1.5 and n of 16 to 25 appear to be optimum to obtain an acceptable height to cell pack length ratio.

I. Original Model 362 Narrow Plate Design. - At the same time the high impact 25 AH cell was being designed, tests of non-impact, heat sterilized cells showed that cells with negative plates larger in area than the positives have better cycle life. Therefore, in order to improve the cycling capabilities of the narrow plate design, the decision was made to place the negative plates outside of the separator U-folds and into slots in the jar wall. Also, the negative structure was changed from 10 mil silver sheet to a chemically milled 48 mil thick core with open area comprising 65-70% of plate area. This type of structure provides a much improved method for retaining the active material. Also, the buckling strength of the milled silver core is 2.5 times larger than that for 17 mil zirconium sheet thus improving the column buckling strength of the plates in the jar wall slots. The Model 362 cell pack was designed with 19 negative plates, 18 positive plates, 8 layers GX separator material, and 1 layer E-1488 polypropylene absorber. Table II lists the pertinent electrochemical and structural design factors for the 25 AH narrow plate cell pack.

J. Experimental Nine Plate Cells - Model 362X. - Four non-sterile, high impact 9-plate cells were constructed for design verification tests at 4000 "g" in thick walled Lucite jars. The cells contained 4 wrapped positives with 17 mil zirconium cores and 5 negatives with the 48 mil etched silver grids. All parts except the case met the requirements of the Model 362 cell drawings. All four cells developed excessive hydrogen pressures on formation charge requiring continuous venting. The diagnosis was hydrogen gassing at the Ag grid to Zn metal couple in the negative plates accelerated by the massive etched Ag grid structure. Input was 94% of theoretical Ag capacity; output at 2.4 amps (C/2 rate) was 5.9 AH minimum equivalent to 1.06 C in the full size Model 362 cell. Three of the cells were shipped to JPL for shock tests.

Shock test levels at JPL ranged from 2100 "g" to 2400 "g" with pulse durations of approximately 1 msec at velocities from 93 to 102 feet per second. The cells were shocked in three attitudes: (1) perpendicular to the plane of plates, (2) with the plates hitting edgewise, and (3) terminals forward. High speed motion pictures were made of each shock in order to visually observe plate movement. The only shocks resulting in major damage were with terminals forward at impact levels in excess of 2200 "g". Shocks perpendicular to the plane of plates and edgewise at 4000 "g" levels did not result in any visible damage. Figures 4 and 5 illustrate plates of cell S/N 3 shocked at 4000 "g" with terminals forward showing extensive damage to the positive struts and to the negative grid. The positive plate struts clearly buckled, and the positive plates moved upward in the cell. This upward movement of the positives resulted in loss of support for the adjacent negatives thus causing damage. Clearly, additional support was needed to prevent positive plate buckling which would have in turn offered additional support to the negatives.

The single cell retained at ESB for electrical cycling tests lost capacity steadily through 5 cycles. Reference electrodes showed that the negative plate was indeed the limiting electrode. Positive plates delivered 0.41 AH/gAg at reasonable voltages. The problems of gassing and capacity loss were critical, and a study of amalgamation techniques to be used on negative grids was initiated.

K. Model 362 Design Modifications. - Based on impact and electrical testing of the experimental 9 plate cells, the following two major problems arose requiring redesign:

- Buckling of the 17 mil zirconium positive plate struts.

- Gassing of the cell during formation and subsequent charges.

The buckling problem was resolved by two modifications: (1) increasing the zirconium strut thickness from 17 mils to 37 mils thus increasing buckling strength by a factor of approximately 10, and (2) introducing

PPO 534-801 shims between every positive strut to reinforce any strut which began to buckle.

The method used to reduce hydrogen evolution from the surfaces of negative, etched Ag grids was preamalgamation with mercury prior to adding the negative mix. The mercury amalgamation was done in a plating solution of 5 g potassium iodide, 5 g mercuric iodide, 1000 g distilled water. The grids were suspended from a metal bar (parallel connection) and then immersed in the plating solution between two vertical columns of pure mercury contained in microporous PVC tubes. Electroplating at 0.1 amp per grid was continued to a theoretical deposition of approximately 1% by weight. Weight analysis confirmed that deposition was quantitative. Visual inspection by microscope at 10X to 80X showed a matte finish over the entire grid surface including the etched out surfaces. Three plate cell packs (2 wrapped positives, 1 negative) were fabricated with negatives both amalgamated and unamalgamated and were given a formation charge and discharge. The cell with unamalgamated negatives began gassing at 25% capacity input and gassed through the remainder of charge. The amalgamated negatives gassed only at the end of charge. Discharge capacities at 0.1 amp/in^2 were almost identical, 2.58 and 2.59 cycle. This proved that mercury preamalgamation was beneficial in reducing gas evolution in the high impact cell.

L. <u>Final Model 362 Narrow Plate Design</u>. - The design modifications introduced due to test results on the experimental 9 plate 362X cells were incorporated into the final Model 362 design, and fabrication of prototype cells was begun. The final plate designs are presented in Figure 6, and a pictorial view of the Model 362 cell is shown in Figure 7. Molded jars, subcovers, covers, and vent plugs were procured and immediately tested for heat sterilization capability and burst strength. Eight sealed cases containing 160 cc's of electrolyte were successfully heat sterilized 72 hours at 135°C with no leakage and were then burst tested. Mean burst pressure was 84 psig with a pressure range of 68-94 psig.

Assembly of 12 prototype Model 362 cells was per print and process specifications without dimensional conflicts or sealing problems. All survived 72 hours heat sterilization at 135°C without visible leakage. On the subsequent charge all cells began to bulge immediately after start of charge and were vented when bulging reached 100 mils, after 2 hour charge time. The cells remainder vented overnight and were resealed with pressure gages. During the remainder of the formation charge, only one of 12 cells developed sufficient pressure (46 psig) to require venting.

A summation of the formation cycle data is given in Table III. Average charge acceptance was 0.41 AH/gAg. Discharge capacities at the 12 amp rate ($\sim$ 17 watt load) were 0.30 to 0.40 AH/gAg, acceptable but more variable than desired. Second cycle input was just about the same as the previous discharge capacity.

Eight of 12 cells were shipped to JPL for shock tests in the range 2000 to 4000 "g". Four cells were retained at ESB for automatic cycling at 50% depth as non-shock controls.

M. <u>Cycle Life Tests of 25 AH High Impact Cells</u>. - JPL specification objectives were a 12-cell battery package delivering 400 watt-hours rated capacity with a capability of 90 charge/discharge cycles at 50% depth after 4000 "g" hard landing. Figure 8 presents average electrical data of four non-shock prototype cells. Single cell plateau voltage is 1.45 volts at 12 amps which for a 12-cell battery would be in excess of the 200 watt power requirement. Five second pulse voltages taken initially and at 40% depth of a 12 amp discharge show that the high impact cells are able to sustain the 2C discharge rate quite well. To reduce total testing time required to reach ninety 50% depth cycles, the specification cycling profile of 10-hour charge/14-hour discharge was changed to 10-hour charge/2-hour discharge by increasing the discharge energy at the high rate (200 watts) from 33.3 to 201.6 watt-hours per 12 cell unit. Out of the four prototype cells in the series group, the first two cells failed by zinc penetration at cycles 72 and 75 respectively. The third cell failed by capacity at 121 cycles, and the test was terminated.

In conclusion, the cycle life of this high impact cell design appears to be 70-125 cycles in a wet-charged life of 5-6 months including 72 hours heat sterilization at 135°C in the wet, uncharged state. The separator system consists of 1 layer Kendall E-1488 and 8 layers Southwest Research Institute GX. Since the high impact design requires the negative active material be retained within the pocket type negative grid, the ratio of ZnO/Ag active material by weight is restricted to 0.8 in the cell pack design. Post-mortem of these cells showed negative plate erosion from top to bottom although the teflon matrix remained in the etched pockets of the grid. The low ratio, the downward erosion pattern and resultant densification contributed to failure at 72 cycles by zinc penetration.

After completion of the cycling tests, all development effort at ESB on the high impact 25 AH cell was terminated. JPL retained the eight prototype cells on hand for further electrical and impact testing.

Table I lists the accomplishments observed for the 25 AH narrow plate design as compared to the specification objectives. The completed design has an energy density of 21.5 watt-hours per pound (1.6 watt-hours per in^3) on a per cell basis.

II. DEVELOPMENT OF 5 AH HIGH SHOCK CELLS AND BATTERIES

A. Objectives and Previous Accomplishments. - The original design objectives were controlled by JPL Specification GMP-50437-DSN-C which required a capability for heat sterilization for 120 hours at 135°C, charge, pre-flight tests, launch, and 8 months float or charged stand during interplanetary travel, a hard landing impact of 2800 ±200 g from 113 ±2 ft. per second, and at least four 100% depth cycles. The final objective was an 18-cell battery capable of delivering 5.0 AH at 300W at a minimum voltage of 22.5 volts at a minimum energy density of 15 WH/lb. over the temperature range 10°C to 55°C after the hard landing shock.

Prototype cell design was described(2) in detail and comprised molded PPO 531-801 cell case, sub cover, and overlapping cover, perforated 10 mil Ag sheet plate structures, a separator system of 1L EM-476 and 4L SWRI-GX wrapped on 6 positive plates, and 1L EM-476 polypropylene mat on each of 7 negative plates. Expected performance was 6.8 AH at the one-hour rate, a weight of 0.5 lb., and an energy density of 18.0 WH/lb.

B. Shock Tests on First Generation Non-Sterilized Engineering Models. - While awaiting delivery of molded cell case and cover parts, three engineering cells were constructed for shock tests without heat sterilization. One variation was introduced. Ag sheet core structures in positive plates were replaced with titanium core structures. Two 100% depth cycles were performed before shock tests. Mean capacity was 4.84 AH. Each cell was shocked at 2840-2890 "g" with peak impact observed at 3500 "g" during the shock period of 1.1 millisecond. After shock pulse voltages at 20A load were monitored and then the cells were discharged at 5A followed by 1A to 1.20 volts. The terminals forward axis was the axis of major voltage and capacity loss:

Shock Vector	Cell S/N	Voltage Drop at 20A	Capacity
		mv	AH
-Y	3	260	2.68
+Y	5	180	3.20
+X	4	160	3.34
None			4.84

Cell 5 shorted on recharge, but the capacity of cells 3 and 4 increased to 5.27 AH on the cycle after shock and completed 11 cycles before end of life. Dissection of all cells revealed buckling of the weaker Ag core structure of the negative plates (weight 10 g) while the titanium core in the positive plates (weight 6.3 g) survived the impact. This test verified the stiffness factor of titanium is most desirable for supporting plates of non-heat sterilizable prismatic AgO-Zn cells. Capacity losses due to shock were attributed to loss of active material in negative plates from contact with the plate grid - recoverable on the subsequent cycle.

C. Prototype Heat Sterilizable 5.0 AH Cells. - For the combined requirement of heat sterilization and high impact, 5.0 AH cells were fabricated incorporating molded PPO 531-801 cell cases, covers, subcovers and plate structures reinforced with silver sheet. Case to cover seals were evaluated by burst tests: 160 ±24 psig with overlapping cover as compared to 60 psig without overlapping cover.

Eleven cells were sealed and heat sterilized for 120 hours at 125°C. A.C. impedance dropped significantly with sterilization, ranging from 230 to 560 milliohms before to a range of 35 to 71 milliohms after sterilization. After a mean formation charge of 7.02 AH, the cells were discharged first at 5A and then at 1A to 1.30 volts per cell. Mean voltage and discharge output was 1.44 volts and 3.60 AH at 5A and 1.53 volts and 0.65 AH at 1A. On recharge the net input increased to 7.30 AH. Six cells were shipped to JPL for the high shock tests. Table IV summarizes JPL shock data, pulse voltages after shock, and the residual discharge capacities. When compared to the 5 cells which were not shocked but discharged in the same manner, capacity loss due to shock was found to be 27-30%:

Test Condition	Sample Size	Discharge Capacity - AH to 1.30V 3.3A	0.7A	Total
No Shock	5	3.95	0.38	4.33
2,380 - 3,150 g Shock	6	2.75	0.30	3.05
Capacity Loss, %		-30	-27	-30

Post shock visual examination revealed no damage to the cell exterior or seal. X-rays before and after shock were compared critically. In the terminals forward direction plate struts buckled severely at 3,050 g - but only slightly at the 2,410 g level. In lateral shock with positive terminal cell edge forward and a 3,150 g level, plates buckled severely. Both cells with shock greater than 3,000 g shorted prior to or just after the 3rd cycle.

Prototype cells were therefore accepted in design review for shocks up to 2,400 g level, but for all higher shock levels plate structures would require other materials or support techniques to obtain the desired stiffness.

D. High Shock 5.0 AH Cells for CSAD. - An immediate application for the 5.0 AH heat sterilizable high shock cell was as a 12-cell power supply aboard the JPL Capsule System Advanced Development (CSAD) landing module.

Production methods were controlled and parts were made to tight tolerances. Activation of cells was modified to eliminate washing of negative plates adjacent the activation hole and quantities of electrolyte were controlled to 21.0 ± 0.3 cc per cell, leaving a free volume at seal of 4.3 ±1.2 cc. Electrolyte concentration was decreased to account for the measured diffusion of water vapor from the cells during 120 hours sterilization at 135°C: 8.0 - 8.9 mg water per hour through 11.2 in^2 PPO 531-801 with thickness 0.10 inch.

Figure 8 is a cut-away view of the cell design (ESB Model 344). Figure 9 gives typical performance at the 5 and 1 hour discharge rate and voltages as a function of load to 10 amperes at 75 ±5°F.

For system and drop tests 120 cells were fabricated and delivered to JPL. JPL selected cells for 12-cell batteries by matching pre-heat sterilization a.c. impedances and as manufactured(uncharged) open circuit voltages. Each matched group of 12 cells was potted into an aluminum chassis with epoxy as a 12-cell battery. The selected battery was then heat sterilized 24 hours at 125°C, checked out for leakage, installed in the CSAD spacecraft(3), sterilized in the landing capsule a second 24 hours at 135°C, and then charged as a part of pre-flight tests.

In the first drop test on a dry lake bed the 63-1/2 pound capsule fell in free fall from an altitude of 250 feet impacting at 80 MPH (117 feet per second) in the sand at a calculated 1300 g. A second test performed on the same landing capsule with another battery yielded an impact of 2400 g on a macadam surface. After each impact the 12-cell batteries delivered their rated 5.0 AH capacities and performed their mission requirements.

E. High Impact 5.0 AH Cells with Epoxy Platelock. - CSAD type cells were needed with a reliable shock capability of 2800 ± 200 g in any axis. Tests described previously showed plate tabs buckled worst in the terminals forward or lateral shock axis. An epoxy platelock was therefore incorporated to cement the bottom edges of the exposed negative plates and the positives wrapped in the separator "U" folds. A volume of 2 cc epoxy (DEN 438-EK85/DMP30) was spread over the 5.0 AH (Model 344) jar bottom, the cell plate pack inserted, and the assembly cured at room temperature. With negative plates anchored to the jar bottom, impact forces would be controlled in tension in either the + Y or - Y direction and lateral movement would also be restricted. A further restriction in motion was accomplished by wedging polysulfone shims between adjacent positive and negative plate tabs above plate active material.

Seven 5.0 AH cells were constructed with these modifications and were heat sterilized with two control cells for 120 hours at 125°C in air rather than nitrogen, with outer cell case and cover surfaces coated with silicone.

One of seven cells developed oxidative craze lines through a thin portion of the silicone protective coating. The other cells passed the visual test after sterilization. During the second stage of formation charge six of six modified cells developed high pressure and leaked electrolyte while the two control cells behaved normally.

Two cells which lost no more than 0.3 cc out of 22 cc of electrolyte were then equipped with pressure gages and overpotted. During 3 months of cycling the two control cells completed 13 and 15 cycles at 100% depth to failure while the two cells with platelock and shims gave low capacity and shorted after 1 and 2 cycles respectively.

Post-mortem analysis showed silver and zinc penetration through four layers of GX as the control cell mode of failure while the platelock cells shorted through holes in the "U" fold bottom corners adjacent the epoxy. Epoxy was also found to have wicked up the polypropylene retainer folds reducing negative plate area. Since previous tests showed no chemical incompatibility between epoxy DEN 438EK85 and Catalyst DMP 30, physical stresses must have caused the cuts in the GX separator system.

It was concluded that the DEN 438EK85/DMP 30 platelock could not be successfully incorporated unless the increase in hydrogen evolution from the negative plates could be eliminated and greater protection for the GX separator dipping into the platelock could be reliably obtained. Development of the high impact cell was therefore redirected toward massive chemically etched Ag grid structures.

F. Battery Development. - JPL Specification GMP-50437 required development of a 120 WH battery capable of surviving a 2800 ± 200 "g" hard landing impact and then delivering 300W, 5.0 AH, at voltages above 22.5 volts.

A paper design plus stress and weight analysis was performed on the assumptions:

- 9-cells of Model 344 CSAD high impact design in each of two batteries in series connection.

- Cells potted into aluminum honeycomb with flange mounting top and bottom for between deck mounting in spacecraft.

Each 9-cell battery then had dimensions overall of L 7.00, W 5.50, H 4.00, volume 154 in^3, weight 8.3 pounds, and an energy density of 7.8 WH/lb. of battery delivered at the 130W rate. The energy density of 5.0 AH CSAD type cells was 14.4 WH/lb. at the same rate. Projected energy density penalties for chassis structure were therefore as high as 46%.

G. Material Compatibility. - Maintenance of the desired physical and chemical characteristics of all cell components without interaction losses was essential during and after 100 hours heat sterilization at 135°C in the sealed state in an atmosphere of pure nitrogen. Extensive tests were performed with a final check out in a 10 AH sealed Ag-ZnO cell. Table V gives the cell design features tested in the final design material list. Cell case and cover materials, sealants, separator system, lead insulation, and sealing processes were investigated before selection of optimum materials.

Jar Cover, Subcover, and Case Material. - General Electric Company polyphenylene oxide was selected for cell tests. PPO 531-801 was found to craze when exposed to oxygen in air during heat sterilization. PPO 534-801 was substituted to reduce crazing in air. Cell capacity was 5% higher with PPO 534-801 cell cases.

Epoxy Sealants. - Of the epoxy systems tested the following systems were judged satisfactory in cell tests: Dow DEN 438EK85/DMP-30; Epocast 31B/9216; Epocast 221/927; and Isochem 811A811B. The last three were accepted for production processes. Exposure in cells of these epoxy seals up to 2.8 in^2 in area to 100 hours heat sterilization at 135°C, changed discharge capacity in nine cycle cell tests not more than ±5% from control cells with no exposed area.

Separator Systems. - Non-woven polypropylene was selected as an electrolyte absorber between the positive plate and the semi-permeable membrane and as a retainer to hold zinc oxide active material onto negative plate grids. Introduction of sintered teflonated negative plate processes reduced the need for retainers in most cell designs. Kendall E-1488 (EM-476) material was used in most cell applications. Semi-permeable membranes were Southwest Research Institute GX, polyethylene film grafted with acrylic acid and cross-linked with divinylbenzene, and Radiation Applications Inc. P-116 polyethylene film. Table VI compares the physical characteristics of the two materials when tested at receiving inspection. Tests of design variations of the 10 AH cell yielded the following responses on discharge capacity at the C/3 rate:

• 6L RAI-116	7.90 AH	
• 1L EM-476 Absorber, 5L GX	7.52	- 5%
• 6L SWRI-GX, no absorber, no retainer	5.91	-25%
• 1L EM-476 Absorber, 5L GX, & 1L EM-476 Retainer	5.14	-35%

Plate Lead Insulation. - Flexible thin walled plate lead insulation was used to cover .016 in diameter plate lead bundles. Raychem RNF-100 irradiated polyolefin passed material heat sterilization tests and was attractive because of choice of color for coding. In 10 AH cells, however, hydrogen evolution on formation charge increased enormously in cells heat sterilized 100 hours at 135°C. Cells bulged in excess of 100 mils and leaked. Substitution of heat shrinkable teflon tubing, while not color codable, eliminated gassing and increased capacity from 5.91 AH to 10.1 AH on formation discharge at the C/3 rate - an increase of 41%.

Heat Sterilizable 10 AH Cell Performance. - After all material evaluation the 10 AH cell weighed 171 ±2 g, had over all case dimensions of L 1.04, W 1.94, H 3.26, and delivered 10 AH at rates up to the 15 ampere rate at 25°C after 72 hours heat sterilization at 135°C.

Rate	Discharge Time	Plateau Voltage	Energy	Non-Impact Energy Density	
Amps	Hours to 1.30V	Volts	WHr	WH/lb.	WH/in^3
2.5	4.2	1.52	16.0	42	2.4
7.5	1.3	1.48	14.8	39	2.2
15.0	0.63	1.42	13.5	36	2.0

A six cell battery delivered 9 cycles of 100% depth and 74 cycles (21 hour charge/3 hour discharge) at 50% depth to failure by zinc migration over the 6L GX separator system during 6 months of wet life.

Using the above performance as a nominal non-high impact heat sterilizable design, the achievement of 2800 ±200 g in the CSAD cell weighing 226 g in the same case decreased energy by 44-46% -

Rate	Discharge Time	Plateau Voltage	Energy	High Impact Energy Density	
Amps	Hours to 1.30V	Volts	WHr	WH/lb.	WH/in^3
1.0	6.0	1.52	9.1	18.2	1.4
5.0	1.0	1.46	7.3	14.6	1.1

H. Requirements of Improved, Second Generation 5 AH Cells. - Following completion of development effort on the Model 344 high impact cell for use in the Capsule System Advanced Development (CSAD) project by JPL, additional effort was added to the existing contract for improving the shock capability of the 5 AH cells and completing development of 18-cell battery units. JPL Specification GMP-50437-DSN-C, dated 28 November 1966, was originally the controlling document for these batteries and included an energy requirement of 120 watt-hours for the 5 AH battery. Later, the requirement for delivering multi-cell batteries was deleted; however, ESB was to continue development of cells required for these batteries. At this time JPL issued Engineering Memorandum 342-70 as the controlling document for design goals of the 5 AH high impact cell. The required shock level for these cells was 4000 "g" peak from an impact velocity of 120 feet per second. ESB's effort was thus directed toward improving the 5 AH CSAD cell in the following areas:

- Increase shock capability from a proven 2200-2400 "g" to 4000 "g" peak.
- Decrease the 44-46% energy losses suffered due to incorporation of the high impact design features.

I. Use of High Strength Metals for Plate Core Structures. - The Model 344 CSAD 5 AH cell employed silver sheet as both the positive and negative plate, high impact, structural material. Since this cell design was capable of only 2400 "g" maximum impact load, it was evident that materials with higher strength-to-weight ratios than silver would be required for a 4000 "g" 5 AH cell. The two metals which were recommended by ESB's Research Center for possible use in heat sterilizable Ag-Zn cells were Inconel 600 and zirconium.

Initial experiments were performed with 9-plate cell packs with Inconel 600 as the core material for both positive and negative plates. Since exposed Inconel 600 metal was known to create gas evolution in the Ag-Zn cell environment, the core structures were electroplated prior to plate fabrication. Positive plates had a silver plate over an underlying nickel flash while the negatives had silver plate over either nickel or copper flash. PPO 531-801 shims were used to maintain normal pack tightness.

During 120 hours sterilization at 135°C seven of seven cells with Inconel 600 exhibited leakage - 5 minor leaks around negative terminals and two major leaks through the case-to-cover seal. Leakage sites were repaired, and after restoring electrolyte lost, cells were sealed and charged. Cells leaked again during the preformation charge, indicating above normal pressures. During charge at 5 ma/in^2 to 1.97 volts the three cells with pressure gages had to be vented periodically at 40-60 psig. Two cells without gages ruptured. After a 24-hour stand, open-circuit voltages dropped as low as 1.0 volt. After this experience Inconel 600 was dropped from further consideration, except to demonstrate the shock capabilities of plates supported with a metal of comparable strength.

Zirconium was first evaluated on a positive plate core structure in Model 281 cells. Negative active material weight was reduced to allow sufficient room for the additional structure. Four cells were successfully heat sterilized 120 hours at 135°C without leakage. Charge acceptance was 9.26-9.56 AH (0.31-0.32 AH/gAg), and output on the two step discharge test was 6.17-6.79 (0.21-0.22 AHgAg). All cells developed pressures in excess of 60 psig during early stages of formation charge. Analysis showed that the gas evolved was hydrogen, therefore, negative limitation and not the presence of zirconium was the indicated problem area.

At the same time of development of the high impact cells, tests on non-shock cells revealed that polyolefin tubing on the plate lead wires was responsible for gassing and poor capacity performance. The initial four test cells with zirconium all had polyolefin tubing which accounted for their poor performance. Two additional cells were fabricated without polyolefin tubing on the plates. In these two cells, the amount of active silver in the positives was reduced to accomodate the zirconium core structures. All other design parameters were identical to control Model 281 cells with no polyolefin tubing. First cycle discharge capacities of the two cells were 7.0 and 6.5 AH (0.28-0.30 AH/gAg) and mean plateau voltage was 1.49 volts at 3.3 amps. Two Model 281 control cells being tested simultaneously yielded 9.9 and 10.6 AH (.34-.36 AH/gAg). There was no pressure buildup in any of the cells indicating the problem of gas evolution was eliminated. These results show a 12-22% loss in capacity due to the presence of the zirconium core structure. This degree of loss had to be accounted for in the final design of the improved 5 AH high impact cell. Reference electrode studies were performed on one of the cells with zirconium structures and showed the zirconium re-inforced positives to be limiting performance - See Figure 10.

J. <u>Negative Plate, High Impact Structure</u>. - As noted previously, the Model 344 cell employed silver sheet as the negative plate core structure and was limited to a maximum shock load of 2400 "g". Additional strength was therefore required to raise the shock capability to 4000 "g". High strength metals, such as Inconel and zirconium, were investigated for use as the negative plate structure; however, these materials were rejected because of their tendency to evolve gas while in contact with zinc. Electroplating of these metals was considered and rejected because the plated surfaces would have to be completely devoid of pin holes to prevent reaction between zinc and the underlying metal. The core structure finally accepted for use was a chemically etched silver grid whose thickness is nearly as great as the total plate thickness. The etched-out area of grid is 65-70% of the total plate area and provides pockets for retaining the active negative mix. The design thickness of the grids in the 4000 "g" high impact 5 AH cell was fixed at 37 mils which increased the buckling strength of the core structure by a factor of eight as compared to 10 mil silver sheet. In the vunerable strut area of the negative, the buckling strength was approximately doubled. Also the negative plates were designed to fit into slots in the jar wall to reduce the moment forces at the juncture of the plate core and structure.

Because of the massive volume of exposed silver metal in the etched negative grids, the tendency was for hydrogen gas to be evolved on the negative. The approach used to reduce or eliminate this gas evolution was premalgamation with mercury of the silver grids. Section I, Paragraph J of this report covers the experimental work undertaken to reduce gassing of the negative grids by mercury amalgamation. The same procedures used on 25 AH cells negative plate grids were employed with the 5 AH cell etched grids. These amalgamation procedures were shown to substantially reduce gassing of the negative silver grids.

K. Procedures for Applying Negative Active Material. - The procedure finally adopted for applying negative active material to expanded silver grid in heat sterilized cells is to press the dry, teflonated powder onto the grid and then sinter the plate at 325°C to form a teflon matrix. If the high shock negative plates were made by this process, the massive silver core would be exposed to the 325°C temperature thus reducing its tensile strength by annealing.

An experiment was conducted to measure the effect on the tensile strength of 10-mil Ag sheet of -

- Mercury amalgamation (.0001 inch layer)
- Sintering at 325°C for 1 hour dry.
- Heat sterilization at 135°C for 72 hours.

Test specimens were machined to a tensile paddle configuration and then, after the specified treatment, pulled to failure on a Dillon tensile tester at a strain rate of 0.25 inch per minute. Table VII data reveals the worst to least reduction in strength is attained from the treatments:

sintering > sterilization > amalgamation

Electroplating a mercury coating of 0.1 mil (total for both sides) in 10-mil did not decrease silver sheet tensile strength significantly from pure Ag controls. It was concluded that a non-sintered negative process would have to be used in the high impact negative plates and that designs should include a maximum Ag yield strength of 25,000 psi.

The process developed for applying the negative mix to the etched silver grids consisted of:

(1) Preparing the negative mix using a liquid dispersion of teflon particles (designated T-30) and deionized water.

(2) Spreading the wet mix into stainless steel drying trays.

(3) Sintering in an oven until the mix temperature reached 325°F.

(4) Chopping the dry cake into small, teflonated particles.

(5) Pasting of the material into the etched-out cavities of the negative grids.

This procedure eliminated sintering of the negative grid; however, the grid was later required to undergo heat sterilization at 135°C. Therefore, the maximum tensile yield strength of the grid after heat sterilization was only 25,000 psi.

L. Final Model 361 High Impact 5.0 AH Cell. - Incorporating all the data available on plate structures, plate fabrication, shock and cycling tests, the final 5 AH high impact cell design included:

- 17 mil positive plate structures with 37 mil thick support struts.
- 37 mil chemically etched silver grids including struts. Negatives to fit into jar wall slots.
- Mercury amalgamation on the etched silver grids (1% by weight).
- 8 layers SWRI-GX separator material but no positive plate absorbers.
- Negative active mix presintered and then pasted into etched silver grids.

Figure II presents a pictorial layout of the final Model 361 design. This design is controlled by ESB Drawing 361-2000.

Development testing during fabrication and parts acceptance included burst pressure tests after heat sterilization 72 hours at 135°C on dummy cells having no plates but case and cover seal per final assembly drawing. Eight assemblies gave low (median) high burst pressures of 125 (149) 178 psig. Case failure occurred in the broad jar walls with cracks developing along the vertical jar corners.

Twelve Model 361 prototypes were assembled in the final design, heat sterilized 72 hours at 135°C, and formation charged. All cells successfully survived heat sterilization in air with no electrolyte leakage. During formation charge without clamps for support, the maximum cell case bulge was 18 mils indicating relatively low cell pressures at this crucial stage. Table VIII presents the formation charge and first cycle discharge for the 12 cells. Charge acceptance was 10-20% lower than expected on an average. Discharge efficiencies were 0.26-0.31 AH/gAg which is 14-25% lower than non-impact cells. Ten of the cells were shipped to JPL for impact testing in the range 2000 to 4000 "g".

Table IX presents cycle 1 to 4 electrical data for one of the cells retained at ESB. Performance after cycle 1 was only 60% of expected. The postulated explanation was the absence of a positive plate absorber and free electrolyte over the entire areas of the positive plates. The 25 AH high impact cells being developed simultaneously with the Model 361 cell had very similar plate designs and included positive plate absorbers. Their electrical performance was quite good. (See Table III).

Only one shock test had been performed at JPL at the termination of this contract, and that test was performed with the cell in the terminals - aft attitude. The cell survived a 4000 "g" shock with no apparent damage. However, previous experience has shown that terminals-aft shocks are the easiest to survive.

Table X summarizes the Model 361 cell accomplishments versus specification requirements. The cell energy density obtained was 10.6 watt-hours per pound (0.9 watt-hour/in^3).

III. DEVELOPMENT OF 70 AH CELLS AND BATTERY

A. Objectives. - Initial objectives of this 12-month program was to design, fabricate, and test 80 AH cells to the requirements of JPL Specification GMP-50607-DSN, and then design, test, and manufacture for delivery four 24-volt 80 AH wet heat sterilizable batteries.

During the program work was redirected, eliminating battery development at ESB, concentrating on cell development, and requiring delivery of 100 cells in June 1969. JPL Memorandum 342-71 defined cell requirements for an ultimate 12-cell 1200 watt-hour battery capable of sterilization for 120 hours at 135°C, pre-flight check-out, spacecraft launch, 9 months inter-planetary travel, and four 100% depth cycles after landing. Environments which required major design considerations were:

- Pyrotechnic shocks, 30 total, 250 g for 0.7 ± 0.2 milliseconds.
- Vibration-entry, 35 grms, 100 to 2000 Hz.

B. Engineering Model Cell Tests. - Cell design was completed and nine 80 AH cells were fabricated. Clear polysulfone windows were cemented into the opaque PPO 534-801 jar walls of four cells to observe electrolyte level during sterilization and later cycling. During heat sterilization 120 hours at 135°C in N_2 leakage was observed in 3 cells - at the cover to jar seal of two cells, and at a polysulfone window of the third. Electrolyte loss was 1, 4, and 14 cc. Non-leaking cells registered a diffusion loss of 1 gram as water. The six sterile cells were then cycled with 3 non-sterile control cells. Table XI summarizes mean, minimum, and maximum energy delivered on each of four cycles at the C/4 rate of discharge.

The cell capacities were more variable in the sterile group, but means were almost the same. During formation charge at 5 ma/in^2 (0.93 amperes) to 1.97 volts per cell gas pressures observed on the 6 sterile cells rose to 15 psig in the first 13 hours and a maximum of 35 psig on any cell in 110 hours. Non-sterile cells gave a maximum pressure of 8 psig.

The pressure gages were removed; the 6 sterile cells were resealed and potted with low density epoxy into an aluminum battery chassis as 2 rows of three cells each, simulating 6/18 of the ultimate battery. Vibration tests at JPL exposed a major design defect - tensile failure of the plate grids at the solid sheet to expanded mesh interface along the top edge of each plate. Broken and protruding grid wires shorted two cells.

A subsequent evaluation of grid designs led to: (1) prototype design expanded mesh grid completely framed with a rigid "U" shaped channel covering the grid wire projections along plate edges, and (2) reinforced tabs which passed ± Z and ± Y axis vibration tests.

C. Sterilization After Cycling Tests. - After five 100% depth cycles the three 80 AH non-sterile cells which were not vibrated were discharged to equilibrium open circuit voltages of 10, 15, and 20 millivolts, and then sterilized 120 hours at 135°C in N_2. Figure 12 shows a mean loss in performance of 30% for three cells comparing cycle 5 before with cycle 6 after heat sterilization. Subsequent tests were to show that cycling before heat sterilization or between heat sterilizations is possible if the let-down discharge is terminated at 100 millivolts and if the charge after sterilization is conducted at a very low rate the first 24 hours.

D. Sterilization of Dummy 18-Cell Battery. - A full size 2000 WHr chassis was designed and procured in 6061-T6 aluminum. Eighteen dummy cells were made without plates, activated, and potted into the chassis to evaluate the effect of 120 hours heat sterilization at 135°C on combined interactions of PPO 534-801 cell cases, two cell case-to-cell cover sealants, Stycast 1090/Catalyst 11 potting material, and silver plated copper terminals and inter-cell connectors. Examination after sterilization revealed a 10 gram weight loss, electrical leakage to ground, and a 40 mil extension in chassis length.

The battery was then stored 4 days at -7°C, the lowest storage temperature expected during life, and reexamined. Cracks were found in the Stycast 1090 encapsulant in the vicinity of sharp metal corners. Complete disassembly exposed 5 of 18 cells leaking electrolyte at cell case-to-cell cover interfaces. Cross-section cuts showed leaks occurred where epoxy was wiped off mating surfaces during the act of sealing. No PPO 534-801 material failure was observed. It was evident from this test that differences in the expansion coefficients listed below and the temperature change from +135°C to -7°C were creating major stresses.

Aluminum 6061-T6 Chassis	14.1×10^{-6} in/in°F
Stycast 1090/Catalyst 11	10.6
PPO-534-801	29.0
Ag Plated Copper	9.8

Corrective action was instituted to relieve stresses and to further reinforce the chassis to eliminate the 40 mil extension in battery length.

E. Prototype Cell Design. - Engineering model cells were redesigned to increase wet life in the charged state to 18 months, to eliminate the vibration mode of failure at 30 grms, and to improve a plate alignment problem when potting plate tabs into cover wells. Table XII contrasts the engineering cell and prototype cell parameters.

Dummy cells were also sealed with four test case-to-cover sealants, sterilized, thermally shocked down to 0°C, and then burst with hydraulic pressure. Five of 6 cells sealed with DOW DEN438EK85/DMP-30 leaked through craze cracks in the epoxy seal. Six of 6 of the best epoxy survived all treatment with no leakage and burst unsupported at 60, 70, 70, 75, 125, and 136 psi with failure beginning at thin sites in the molded jar walls. Epocast 31B (Furane Plastics Incorporated) with hardener 9216 was incorporated in the final seal design.

Plate tab sleeves and coatings were also evaluated. The optimum performance was obtained from FEP sleeves flattened and placed over the plate tabs.

Nine prototype cells were constructed according to ESB Drawing 364-2000 and all referenced documentation. Six cells were successfully heat sterilized 72 hours at 135°C in N_2. Water loss through the case ranged from 1 to 2 grams of 227 grams electrolyte in the cells. Electrolyte level viewed in one cell through a clear polysulfone window was at 86% of plate height after heat sterilization. During formation charge cell pressures were monitored on compound gages installed after heat sterilization. Maximum pressure was 15 psig, mean pressure 8 psig, during the entire charge.

The six sterile cells and three non-sterile control cells were then discharged at 20 amps to 1.25 volts. Non-sterile cells delivered 7.4% less capacity, a difference significant at the 95% level of confidence on a Student t test. The six sterile cells were then charged partially, potted into an aluminum chassis with Stycast 1090 epoxy, and shipped to JPL for full environmental tests. The non-sterile cells were cycled to determine discharge capacity as a function of rate at 2, 20, 35, and 70 amperes to 1.25 volts. Figure 13 gives the voltage versus discharge capacity plots of the median cell of three at these rates.

At JPL the six cell battery was subjected to sweeping sine vibration of 5 g-17 to 50 cps, 15 g-50 to 100 cps, and 35 g-100 to 2000 cps. During vibration fluctuating open-circuit and loaded voltages were observed on the cells. The only test variable was the sleeving on plate tabs to insulate plates of opposite polarity. It was observed that voltage under 40A load varied most on cells with no sleeving and least on cells with sleeving on all plates.

Sleeving Location	Cell S/N	Open Circuit Voltage	Loaded Voltage-Volts 10A	20A	40A
No Sleeving	13,14,15	Low	1.52	1.37	1.14
Sleeves on Positives	16	Normal	1.54	1.47	1.25
Sleeves on Negatives	17	Low	1.64	1.45	1.23
Sleeves on Positives and Negatives	18	Normal	1.63	1.47	1.34

It was concluded that production cells would have 10 mil FEP sleeving on all plates to provide insulation and greater stacking pressures between plate tabs.

F. Cells for Storage Tests. - Twenty-seven 70 AH cells were manufactured to ESB Drawing List 364, Revision F, preformed, sterilized 72 hours at 135°C in nitrogen, and then cycled through two cycles. Table XIII gives the minimum, mean, and maximum observed in a sample of 27 cells during each of these tests. On the cycle 2 discharge at the C/4 rate (17.5A to 1.25 volts) mean energy density was 53 WH/lb and 3.7 WH/in^3. Figure 13 summarizes voltage versus capacity curves for this cell design for both prototype cells and reliability cells.

Twenty-two cells were divided into three groups to evaluate wet life on charged stand, discharged stand, and on float charge at 1.87 volts per cell. Tables XIV, XV, and XVI summarize trends observed during the first 31 days of test at 72 ±3°F. No sustained pressure rise was observed in cells with pressure gages during the storage tests.

Work on this task was terminated by Modification 24 of the contract. All cells under test were shipped to JPL with no failures on stand observed to that date.

Table XVII contrasts achievements versus specification requirements at the time of termination.

IV. DEVELOPMENT OF 25 AH INTERMEDIATE CYCLE LIFE, LOW IMPACT CELL

A. Objectives. - A new high priority task was authorized to develop a 25 AH cell meeting the requirements of JPL Engineering Memorandum 342-68 except the 4,000 "g" impact test. Table XVIII condenses these requirements for the corresponding 12-cell 400 WH battery. Delivery requirements were 20 Type A cells in March, 20 Type B cells in April, 20 Type C cells in May, and 100 final design cells in August, 1969.

B. Cell Design and Test Program. - A 24 AH cell design cycled on another task was modified to give reliably 90 cycles at 50% depth of discharge in a wet life goal of 18 months including 250 g, 0.7 ±0.2 msec shocks and 30 g rms vibration, 16 to 2000 Hz, during launch from earth and entry onto planet. Five groups of 5 cells each were fabricated to test the relative merits of 7L versus 9L GX membrane, Pellon 2530W absorber versus no absorber, positive versus negative wrap, two negative active material densities (42 and 49 g/in^3), ZnO/Ag weight ratios 0.8 to 1.0, and a vibration deadening epoxy plate-lock. Common to all cell designs were the features:

- Molded PPO 534-801 cell case and cover sealed with epoxy.
- Twin 3/0 Ag negative grids spotwelded together with diamond patterns crossed at right angles.
- Mercuric sulfide in negative active material at 4% level.
- Teflonated plates sintered at 325°C for 1 hour.
- 43% KOH containing 114 g ZnO per liter.

One cell of each group of five contained a 3 cc Epocast 221/927 epoxy plate-lock. One cell from each design group was also scheduled for 3 pretest cycles before heat sterilization. All cells were treated with a preformation, charge and wet bake-out procedure just prior to sealing hermetically. This treatment was developed by the ESB resident engineer at JPL and was shown to increase capacity after heat sterilization.(4)

C. Test Group I - No Plate-Lock, No Pretest. - After sealing each of the 15 cells, three from each of 5 design groups, the group was heat sterilized 72 hours at 135°C. Weight loss was 3-6 gms in 3 cells and 1-2 gms in the other 12. Close inspection revealed craze cracks in the DOW DEN438EK85/DMP30 (100:5) epoxy seal were greater in number and severity than in the cells with the normal diffusion loss of 1-2 gms. A parallel investigation of other epoxies was immediately begun to find a non-crazing epoxy with good adhesion to PPO 534-801. Table XIX summarizes data which led to selection of Epocast 31B/9216 (100:10) for the sealant of the final cell design.

Capacity measuring cycles 1, 2, and 3 were performed at 100% depth at room ambient at rates of 2, 8, and 16 amperes to 1.30 volts. Silver utilization was in the range of 0.33 to 0.39 AH/gm compared to a range of 0.35 to 0.41 AH/gm for non-sterile control cells in the pretest group.

Three-cell groups were then cycled at 50% depth for two weeks delivering 2 cycles per day of 10 hour charge/2 hour discharge. Cycling voltages were 1.94 volts per cell constant potential with charge limiting currents set at the C/20 and discharge currents at the C/4 rate:

Design No.	Rated Capacity AH	Load Resistance	Limiting Charge Current at 1.94 V/C Amps	Delivered Capacities-AH Cycle 5	Cycle 25
1	22	0.817	1.14	11.3	11.4
2	20	0.895	1.04	9.9	9.8
3	20	0.883	1.06	9.6	9.7
4	24	0.766	1.22	11.8	11.8
5	26	0.700	1.34	12.2	12.2

At the completion of 36 cycles the cells were placed on a 2-step discharge cycle: high rate for 48 minutes, low rate for 72 minutes. Cycling parameters then became:

Design No.	Discharge Rate-Amps High	Discharge Rate-Amps Low	Delivered Capacity - AH High	Delivered Capacity - AH Low	Delivered Capacity - AH Total	Delivered Energy WHr.
1	12.2	1.13	9.8	1.4	11.2	16.6
2	10.9	1.13	8.7	1.4	10.1	15.4
3	11.2	1.13	9.0	1.4	10.4	14.9
4	13.1	1.13	10.5	1.4	11.9	17.6
5	11.5	3.00	9.2	3.6	12.8	19.3

Table XX summarizes cycle life to failure of first cell in all but one design group and the accumulative ampere-hours output during cell life. Based on maximizing accumulated output during 6 months of cycling the most desirable design features would be:

- Positive wrap 1L Pellon 2530W plus 7L GX.
- 49 g/in^3 density negative active material.

These features were recommended for the final cell design.

D. Test Group II, No Plate-Lock, Pre-Test Group. - Five cells, one cell from each design group, were cycled through three cycles at the 2, 8, and 16 ampere discharge rate before heat sterilization. This data provided a control set for the 15 cells sterilized before cycling. Table XXI compares the median heat sterilized cell with the non-sterile cell of each design group. Based on the 8 ampere (C/3) discharge rate group silver utilization and energy densities were:

Design Group	Discharge Efficiency-$\frac{AH}{g}$ Non-Sterile	Discharge Efficiency-$\frac{AH}{g}$ Sterile	Plateau Volts Non-Sterile	Plateau Volts Sterile	Energy Density WH/lb Non-Sterile	Energy Density WH/lb Sterile
1	.379	.354	1.48	1.50	46.2	43.7
2	.444	.409	1.48	1.50	49.3	46.1
3	.418	.391	1.47	1.50	46.8	44.7
4	.386	.378	1.49	1.49	50.4	49.5
5	.419	.361	1.48	1.50	57.7	50.3
All	.402	.379	1.48	1.50	50.1	46.7
Response Due to HS, %		-5.7		+1.4		-6.8

Figure 14 gives cell voltage versus capacity for the pretest group cells discharging at the C/3 rate. Prior to heat sterilization and after the 16 ampere rate discharge each pretest cell was let down through an 8.2 ±0.8 ohm resistor to a voltage of 0.10 volts in a 40 hour period. Open circuit voltages 30 minutes after removing the load ranged from 0.02 volts to 0.18 volts.

The 5 cells were then sterilized 72 hours at 135°C in nitrogen. Two of 5 cells had electrolyte leaks through cracks in the epoxy cover to jar seal and design groups 4 and 5 lost 2 and 6 gms respectively. This weight of electrolyte solution was added, the cells resealed, and the three cycles before heat sterilization were repeated. Table XXII summarizes discharge efficiencies. The mean loss in silver utilization due to both sterilization (HS) and to the pretest was calculated to be:

No HS	HS	Pretest & HS	Pretest
0	-5.4%	-7.3%	-1.9%

After the six 100% depth cycles the pretest cells were recharged and then placed on automatic cycling. The profile was the same as the last cycles on Test Group I: i.e. 2 cycles per day, 2-step discharge of 120 minutes, charge of 10 hours at a constant potential of 1.94 V/C and current limited to the C/20 rate. Table XXIII summarizes the cycling history of the 5 cells. Designs (-1), (-3), and (-4) failed by negative plate erosion and low capacity at cycles 88, 83, and 69 respectively. Design (-2) shorted at 98 cycles. Design (-5) did not fail. At cycle 51 when the test was stopped, cell capacity was 15.1 AH. Accumulated capacities to failure of the first four of five cell designs are less in the pretest cells by 35, 18, 16, and 15% respectively. The mean effect of the pretest is therefore a loss of 21% of the capacity accumulated over all cycles.

E. Test Group III, With Plate-Lock - No Pretest. - Five cells, one of each design, were fabricated with 3 cc Epocast 221/927 epoxy in the bottom of the cell jar to cement the cell pack to the inside jar bottom. Such a plate-lock had been qualified on a 50 AH sealed battery for a Mariner mission to permit vibration up to 30 grms in the frequency range 100-2000 cps without damage. (5)

Sterilization was performed for 72 hours at 135°C. Three cycles were performed at 8, 16, and 2 amperes to 1.25 volts. Table XXIV summarizes a comparison in the silver utilization in cells without plate-lock to cells with plate-lock. The response was a mean decrease of 14.8% in capacity averaged over the five cell designs and three discharge cycles. The loss in capacity was greatest in negative wrapped cells and cells with the higher density negatives.

The cells were recharged, shipped to JPL for environmental tests per JPL Engineering Memorandum 342-68. Table XXV summarizes the life history of each of the five cells from activation 4-10-69 to 1-23-70, a wet life of 9 months, 13 days. The mean charged stand and cycling loss in 9 months was 3.4% per month which was recoverable on charge and comparable to cells with no plate-lock.

At this time the task was terminated with cycling tests schedued but not completed. The effect of the plate-lock on cycle life was therefore not determined.

F. Production of Cells. - In accord with the contract, 20 cells each of Types A, B, and C were manufactured and delivered to the Jet Propulsion Laboratory for their tests. Delivery dates were 4-18-69, 5-15-69, and 7-23-69 respectively. Selection of the deliverable designs was based on initial cycle performance rather than final cycle life which was not then known. Designs (-3), (-4), and (-5) were chosen. Each has 9L GX and no absorber as the cell separator system. The final design cell was design (-1); however, the task was terminated prior to release to manufacture the 100 deliverable cells. Complete documentation for this cell design was delivered to JPL as ESB D/L 379 - Revision E. A later design incorporating improvements to extend wet life was evaluated with epoxy plate-lock, with a pretest cycle, and a 200 hour heat sterilization on Martin-Marietta Company Contract RC9-841011.

V. DEVELOPMENT OF HIGH CYCLE LIFE LOW IMPACT CELLS

A. Objectives. - Contract objectives were defined by JPL Specification GMP-50436-DSN-B and included development of an 18-cell 1200 WH battery capable of one year prelaunch storage, heat sterilization of 120 hours at 135°C, charge, vibration in frequency 100 to 2000 cps to 35 g, 9-month interplanetary travel, planet entry, deceleration of 100 g for 10 minutes, a landing shock of 200 g for 0.7 ± .2 msec, and then 400 cycles at 50% of rated capacity. Each 48 AH cell was to be cycled at discharge rates from C/10 to C/3 in the temperature range of 10°C to 50°C. Contract objectives were changed during this reporting period deleting battery development, reducing capacity from 48 to a 20 AH cell, and heat sterilization from 120 to 72 hours at 135°C.

B. Engineering Cell Design. - A basic 24 AH cell was designed and drafted as ESB Model 172. Table XXVI lists the major design features and physical characteristics. Fifteen cells were fabricated with modifications in design and testing to evaluate:

- 3, 5, or 7% mercuric sulfide negative plate active material additive.
- Pellon 2530W polypropylene absorber vs no absorber.
- Heat sterilization of 120 hours at 135°C vs no heat sterilization.

Cycle testing included 6 cycles at 100% depth, 34 cycles at 80% depth and 44 maximum cycles at 60% depth at room ambient. Typical C/3 rate discharge at 8.0A to 1.25V gave median capacities for the 3-cell groups of:

Cycle Number	Non-Sterile No Absorber 7% HgS	Sterile Pellon 7% HgS	Sterile No Absorber 7% HgS	Sterile No Absorber 5% HgS	Sterile No Absorber 3% HgS
1	38.8	29.0	33.7	34.7	37.6
6	37.0	25.0	31.0	32.0	36.2
22	27.8	26.8	26.8	26.8	27.4
41	25.0	26.8	26.8	21.6	25.0
61-64	16.0	18.6	17.2	18.6	22.0

Average midpoint discharge voltages of cells having the Pellon 2530W absorber were .02 - .06 volts higher during the first 40 cycles. Sterile cells failed by silver penetration through the 6L SWRK-GX membrane at wet lives of 5.5 to 6.6 months and up to 84 cycles at 60% depth of discharge. Figure 15 summarizes the rate of decay of capacity during cycling tests. Non-sterile control cells lost capacity at a rate of 0.33 AH/cycle reaching 50% of rated C in 82 cycles and failed by negative plate erosion. On the basis of the 24 AH engineering cell tests the following design changes were recommended:

- Reduce mercuric sulfide from 7 to 4% by weight of negative active material.
- Increase layers of SWRI-GX from 6 to 7, 8, or 9.
- Increase ratio ZnO to Ag active material.
- Change from unsintered to sintered teflonated negative plate process (reference 4).

C. <u>Advanced Design 24 AH High Cycle Life Cells</u>. - Special negative plates were fabricated to test scale up of sintered teflonated plates from 5 AH to 24 AH size, two teflon powders (35 micron and 8 micron mean particle size), and various grid structures for as-pressed and sintered-dry strength. In the 24 AH size (2.56 in. X 3.12 in.) with one 2/0 grid (0.20 g/in^2) increasing plate thickness from 20 mils to 78 mils led to delamination of active material during plate handling. Two 3/0 grids spotwelded together with grids crossed gave best overall results in physical tests. The larger teflon particles gave greater as-pressed and sintered strengths under 6 gram metal ball drop tests.

Four cells were fabricated incorporating:

- Teflonated sintered negative plates having dual 3/0 grids and a 29% zinc oxide reserve at full float.
- Negative active mix having 4% mercuric sulfide.
- 6 layers GX membrane separator system with no absorber or retainer.

All other design features were the same as the engineering cells (Model 172). After 72 hours heat sterilization in N_2 at 135°C, the four cells were formed at the 50 hour rate and then discharged at the 8.0 ampere rate to 1.25 volts. First cycle performance was excellent:

Parameter	Unit	Sample Size = 4 Minimum	$\bar{X}$	Maximum
Formation Charge Input to 2.00V	AH	42.5	43.4	44.7
Discharge Capacity (8A to 1.25V	AH	34.1	38.4	41.2
Midpoint Voltage	Volts	1.492	1.502	1.510
Energy Density (Calculated) (1.08 lb/cell)	WH/lb.	48.5	53.6	57.0

During the discharge 5 second pulses were run at currents to 25 amperes (0.25 amperes/in^2) as shown in Figure 16. Voltages were higher at all discharge rates than previous cell designs. Specific resistance of the cell decreased from 32.0 to 25.6 ohm-inches by the design changes. Figure 17 is a sketch of this advanced cell design which was the forerunner of the intermediate cycle life 24 AH cell delivered to the Jet Propulsion Laboratory as the Model 379 cell. Figure 18 shows voltage versus capacity at discharge rates of 5, 10, 17.5, 25 and 37.5 amperes as typical performance for this cell design.

D. <u>Factorial Experiment</u>. - To achieve 400 cycles at 50% depth of discharge required major steps in design and testing to reduce silver penetration, to reduce negative erosion, and to maintain capacity above the 50% rated C minimum. A factorial experiment was designed by the North Carolina State University School of Statistics to test four variables at three levels using 27 cells. Each cell had the common design features:

- 3 full and 2 outside half positive plates with 64 g Ag active material per cell.
- 4 full negatives.
- Negative wrap of 9 layers SWRI-GX separator.
- Sintered teflonated negative active material containing 4% mercuric sulfide pressed-on two 3/0 Ag grids spotwelded with die pattern crossed.

Table XXVII gives the cell design variables and factorial assignments by cell serial number. Negative plates were manufactured with densities of 45 g/in^3 in three thickness groups depending upon the design ZnO/Ag weight ratio - 0.9, 1.2, or 1.5

Electrolyte volumes varied from 48 cc to 65 cc depending upon negative plate thickness and the design wet thickness allotted to the 9L GX membrane - 2.0, 2.4, or 2.8 mils per layer. Values for each cell were calculated on the assumption that under 28 in. Hg vacuum all pores in all plates and separators would be filled with electrolyte and would remain filled when excess electrolyte was dumped by inversion of the cell at 2o in. Hg vacuum. Computer analysis of the adjusted electrolyte weight W in each cell gave the equation:

$$W = 85.98 + .2111(TF) + 5.0778(TH) + 7.0500R + 1.3778K$$

where $TF = (\%\ \text{teflon} - 7)/2$

$TH = (\text{GX wet thickness in mils} - 2.4)/.4$

$R = (\text{ZnO/Ag ratio} - 1.2)/(.3)$

$K = (\%\ \text{KOH} - 43)/2$

and all levels were weighted at -1, 0, and +1. The equation coefficients give the relative order of design constraints controlling electrolyte volume per cell: i.e. R > TH > K > TF in the ratio 7.05:5.08:1.38:0.21. Actual cell electrolyte weights (which were not controlled to a level because of the non-transparent PPO 534-801 jars and covers) agreed to calculated weights within 4.5 grams.

After preformation at the 24 hour rate and seal, the cells were heat sterilized 100 hours at 135°C in N_2 and then leak tested. No electrolyte leakage was observed.

Cells were placed on 100% depth cycling - charging at 0.76 ±.01 amp to 2.03 ±.02 volts per cell, and discharging at 5.3 ±0.1 ampere (c/3 rate) to 1.25 ±.03 volts per cell.

After 15 cycles an analysis of the data by the N. C. State University School of Statistics yielded the following significant effects:

- Decrease in capacity measured by the cycle 1 (C1) discharge capacity minus the mean discharge capacity on cycles 4, 5, and 6 increased with decreasing ZnO/Ag weight ratio.

- Change in capacity between cycles 4, 5, and 6 and cycles 14, 15, and 16: i.e. AV5 - AV15. Tabulation of the means gave:

ZnO/Ag Ratio	C1-AV5 (AH)	AV5-AV15 (AH)
1.5	3.83	1.35
1.2	4.15	-.28
0.9	5.66	.89

Since capacities decreased so drastically, capacity was proposed to be limited by electrolyte. At cycle 46 the cells were discharged at

C/3 rate to 1.25V, then let-down to 0.1 to 0.2 volts per cell, and opened. Electrolyte of the design concentration was added in precise quantities of 5% of the original pre-heat sterilization quantity. The cells were resealed and cycling continued as before. Capacity increased on all but one cell, but much more in cells with ZnO/Ag ratio R of 1.5. The linear effect of R then became statistically significant. Also cells with separator thickness TH = 2.4 and 2.8 had a greater increase in capacity than cells with TH = 2.0 mils per layer of GX. Cycling was continued to short or to 100 cycles of 100% depth, whichever came first. At no time were the effects of electrolyte concentration (41, 43, 45%), membrane wet thickness (2.0, 2.4, 2.8 mils per layer), or teflon (5, 7, 9%) found to be significant over long term cycling.

All cells were then dissected and black and white photographs made of one side of the positive and negative plates and of one of the two "U" folds unwrapped to expose the last (of 9) layers of GX membrane.

Negative erosion of all plates was from top to bottom leaving a dome shaped pattern in the lower 50% of plate area at 100 cycles. Erosion was greater with increasing GX wet thickness allowance and decreasing ZnO/Ag ratio. Figure 19 summarizes visual observations in the dissection; cycles completed, failure mode. Silver penetration increased with increasing membrane thickness allowance and with decreasing electrolyte concentration.

The rapid decrease in capacity with cycling is tabulated from group means below.

Ratio ZnO/Ag	n	Mean Discharge Capacity - AH Cycle 1	Cycle 5	Cycle 38	Cycle 45	Cycle 52	Cycle 100
1.5	7	19.7	16.1	10.9	8.9	12.3	9.2
1.2	9	19.5	15.5	12.1	10.0	11.5	8.4
0.9	8	21.5	15.8	10.1	8.8	9.9	8.1

This capacity loss was attributed to lack of a positive plate absorber to hold sufficient electrolyte to prevent electrolyte limitation on charge.

E. Final Development of High Cycle Life Cells. - Modification 25 of the contract directed concentration on a 20 AH size cell. Building upon the results of the factorial experiment, seven cell designs were drafted and 60 cells manufactured. Variables to be tested included: 2 positive plate absorbers (Kendall E-1488 and Pellon FT-2140), 8 versus 10 layers of SWRI-GX membrane, wedge versus standard shaped negative plates, extended versus non-extended negative plates, positive versus negative wrap, and a spiral wrap. Common design features in all cells were:

- Molded PPO 534-801 jar and cover, and epoxy seal.
- Teflonated and sintered negatives with a minimum ZnO/Ag ratio of 1.5:1.0 by weight.

- 45% KOH saturated with ZnO.

- Four positive plates, 17.8 g Ag per plate at 69 g/in^3 density.

- Five negative plates.

- No shims - cell pack thickness adjustments were made with negative plate active material.

Cells were activated by submerging inverted in electrolyte and pumping down to 29 in. Hg vacuum, then releasing gradually to atmospheric pressure. Cells were then baked out at 100°C for 20 hours in a pressure chamber to remove excess volatiles from all cell components. Excess electrolyte was removed by pumping down to 22 inches vacuum inverted. The final calculated weight was obtained by addition, varying for each design group. Cells were sealed with "O" ring stainless steel plugs and heat sterilized 72 hours at 135°C in nitrogen. Weight losses as water varied as predicted between 0.5 and 1.5 g. Pressure gages were installed in 2 cells of each 5 cell group and all were hermetically sealed.

On formation charge a maximum pressure of 7 psi was observed. The first three cycles were at 100% depth at discharge rates of 2, 8, and 16 amperes. Table XXVIII summarizes by design groups the discharge data for the two high rates and ranks the designs on total energy output and charge-discharge efficiency. High ranking designs had positive wraps and extended edge negatives. The wedge shaped negative design was second best.

For cycling two regimes were selected by JPL on the basis of possible future flight usage:

Regime A: 20 2/3 hour charge/3 1/3 hour discharge.

Regime B: 10 hour charge/14 hour discharge.

Seven 5-cell groups were cycled on Regime A, and five 5-cell groups were cycled on Regime B. Charge voltages for all groups were set initially at 1.95 volts per cell with charge current limited to 0.51A on Regime A and 1.15A on Regime B. Constant resistance loads were adjusted to give an average current of 3.0A on Regime A and 0.70A on Regime B. Target output in each regime was 10.0 AH, representing 50% of rated capacity of 20 AH.

Cycling objective was 400 cycles on each regime or to failure of the third cell in each group of 5. Failure was defined as an individual cell end-of-discharge voltage dropping below 1.20 volts. Tables XXIX and XXX give the status of cycles to failure on both regimes at the end of the contract period. Best three cell designs rated by mean cycle life to failure were:

	Rank	Cycles	Design
Regime A	1	243	Pellon 2140 Extended Edges 8L GX (+) Wrap
	2	220	Kendall E1488 10L GX (+) Wrap Wedge and Extended Edges
	3	199	Kendall E1488 10L GX (+) Wrap Extended Edge
Regime B	1	239	Pellon 2140 10L GX (+) Wrap Extended Edges
	2	218	Pellon 2140 8L GX (+) Wrap Extended Edges
	3	191	Kendall E1488 10L GX (+) Wrap, Wedge Shaped Extended Negatives

Figure 20 shows the decay of end of discharge voltage and end of charge current as a function of cycle life for the best cell design of each regime.

Decay of capacity was measured at 100% depth of discharge at intervals of approximately 50 cycles after a full charge by extending the charge time on each 5-cell group until the charge current decayed to .09-.20 ampere. Charge time did not exceed 24 hours. Each cell was then discharged at the 8.0 ampere rate to 1.25 volts. Figure 21 summarizes the capacity decay rates for both regimes. A major difference in initial decay rates was found between Regime A and B. On the 20 2/3 hour charge/3 1/3 hour discharge, capacity loss was nearly linear versus cycles completed with a slope of 0.3% initial capacity per cycle. On the 10-hour charge/14 hour discharge, capacity decay was 50% in the first 50 cycles. Failure analysis performed on 2 of the first 3 cells failing in each group showed the mode of failure in every case was negative plate erosion. No cells have shorted to date. Photographs of negative plates show erosion from top to bottom in percentages corresponding closely to capacity losses. Thickness measurements and chemical tests showed that active zinc eroded leaving a teflonation matrix behind on the double grids.

It is recommended that the 10-hour charge/14 hour discharge not be used in space unless the constant potential setting of the charger is verified to be sufficiently high to return to each battery at least 3%-5% more capacity than the discharge output on each cycle. Major capacity losses occurred in the first 50 cycles when the experimental setting was 1.95 volts per cell. After increasing c.p. voltage to 1.97-1.98 volts, capacity loss was minimal, but lost capacity could not be restored. No pressure problems were created at the higher setting.

The 20 2/3 hour charge/3 1/3 hour discharge regime in the tests above maintained higher cell capacity throughout wet life.

Cell electrolyte leakage was monitored throughout the eleven month cycling tests. The calculated seal reliability was .883 using the definition of visual observation of carbonate equals a leakage site. Location of leakage and frequency was as follows:

- Around positive terminal to cover seal 4 of 60
- Around negative terminal to cover seal 3 of 60
- All causes 7 of 60

Dissection of seals revealed evidence of radial cracks at locations where PPO 534-801 melt flowed around pins in the mold. Measurements of residual stress with the Skydrol A hydraulic fluid test gave marginal times on the molded covers and acceptable times to craze on covers <u>machined from PPO sheet stock</u>. Improvements in cover design and molding techniques would be essential for flight batteries to obtain acceptable seal reliability.

VI. QUALITY ASSURANCE

A. <u>Control Documentation</u>. - The continuing development of both high-impact and non-impact, heat sterilizable cells resulted in a number of different cell designs. Every design was controlled by a complete set of drawings along with related specifications and standard quality assurance traceability documents. The cell designs may be divided into two groups - those designed and tested for development purposes only and those which were the final designs as required by the various

JPL specification requirements. All cell designs and their corresponding control documentation are listed below:

ESB Model No.	Cell Capacity	High Impact	JPL Specification	Controlling ESB Document
			DEVELOPMENT CELL DESIGNS	
325 A, B, C	30-60	Yes	GMP-50437-DSN-C	D/L 325, Revision G
334	50	Yes	GMP-50437-DSN-C	D/L 334, Revision E
343	25	Yes	GMP-50437-DSN-C	D/L 343, Revision E
380	16	No	GMP-50436-DSN-C	D/L 380, Revision D
172	24	No	GMP-50436-DSN-C	D/L 172, Revision E
			FINAL CELL DESIGNS	
344	5	Yes	GMP-50437-DSN-C	D/L 344, Revision G
361	5	Yes	Engr. Memo. 342-70	D/L 361, Revision D
362	25	Yes	Engr. Memo. 342-68	D/L 362, Revision D
364	70	No	Engr. Memo. 342-71	D/L 364, Revision G
379	25	No	Engr. Memo. 342-68*	D/L 379, Revision E
389	20	No	GMP-50436-DSN-C	D/L 389, Revision B

(*) High impact resistance requirement deleted.

Complete sets of documentation of all final cell designs were delivered to JPL.

B. Major Q.A. Activities. - The following list details the major areas of quality assurance activities undertaken throughout the heat sterilization development program:

- Normal inspection procedures of all development and deliverable cells including acceptance of plates, cell case parts, assembled cell packs, assembled cells, and activation. Material Review Reports were generated for all deviations from the document lists in effect at the time of cell assembly.

- Monitoring design reviews for all cell designs generated and issuing minutes of the review detailing requested changes and follow-up action items.

- Observing post-mortems of cells which had either failed or completed testing and concurring on the findings of the dissections.

- Generation of Quality Assurance Specification No. 251 (QAS-251) to provide traceability and identification of all Model 380 cells fabricated for the 27-cell factorial experiment. This procedure was required since all 27 cells were different in design.

- Inspection of the Data Acquisition System assembled at The Carl F. Norberg Research Center prior to its final acceptance and shipment to EMED.

- Review and sign-off of all engineering notebooks prior to submittal to JPL.

- Development of leak tests procedures for acceptance of cover-to-jar and terminal seals in both dummy cells and fully assembled dry cells.

- Monitoring of SWRI-GX and RAI membrane evaluation to determine their acceptability to existing specification.

- Calibration of heat sterilization oven temperature controllers and also the flow meters controlling the rate of nitrogen flow through the oven.

VII. NEW TECHNOLOCY

During this reporting period U. S. patent applications 758,652 (6), and 758,653 (7) previously disclosed were allowed by the U. S. Patent Office, providing protection for two zinc electrode additives used to minimize positive electrode capacity loss during wet sealed sterilization.

U. S. Patent application (8) 880,250 was filed 11-26-69 and granted December 7, 1971 covering the 5 AH and 25 AH high impact cell construction invented by A. W. Jordan and T. H. Purcell to meet the 4,000 "g" landing impact requirements of JPL Engineering Memoranda 342-68 and 342-70.

TABLE I

OBJECTIVES VS ACCOMPLISHMENT 25 AH HIGH IMPACT CELLS

Design or Operating Parameter		Unit	Objective (1)	Observed
1. Energy Storage (12-cells)		WHr.	400	530
2. Shelf Life Before Use		Yr.	1	NT
3. Mission Environment				
Heat Sterilization at 135°C		Hours	72	72
Space Travel		Mos.	9	NT
Landing Shock, All Axis		g	4,000	4,200 before HS
Landing Velocity		ft/sec.	120	(NT after HS)
4. Cycle Life on Planet		Ea.		
50% depth (10 hr. C/14 hrs. D)			90	72-121
5. Operating Temperature		°C	10 to 55	25
6. Voltage Regulation		Volts		
12 cells (0-200 watts)			14.5 to 22.5	16.8-22.5
1 cell (0-16.7 watts)			1.21 to 1.87	1.40-1.87
7. Discharge Wattage (12 Cells)		Watts	200 max.	770
8. Capacity at 200 W Load (12A)		AH	25	30
9. Mean Cell Voltage at 16.7 watts		Volts		1.48
10. Charging Time, Max.		Hours	72	30-50
11. Cell Dimensions and Volume				
L		in.	--	1.635
W		in.	--	3.200
H		in.	--	5.180
Volume		$in.^3$	--	27.1
12. Cell Weight, Wet, Sealed		lb.	--	2.07
13. Energy Density at Rated Load				
Cell by Weight		WH/lb.		21.5
Cell by Volume		$WH/in.^3$	--	1.6
Battery (estimated)			20	17
14. Automatic Cycling Requirements (Per Cell)				
High Rate Discharge	Time	Min.	10	56
	Power	Watts	16.7	18 avg.
	Energy	WHr.	2.8	16.8
	Current	Amps	--	12.0 avg.
Low Rate Discharge	Time	Min.	830	64
	Power	Watts	1.0	1.12
	Energy	WHr.	13.8	1.20
	Current	Amps	--	0.72
Total Discharge	Time	Min.	840	120
	Energy	WHr.	16.6	18.0
Charge Time		Min.	600	600
Mode		--	c.p.	c.p.
Float Voltage		Volts	--	1.96
Limiting Current		Amps	--	1.30

(1) JPL Engineering Memorandum 342-68 Design Requirements, Heat Sterilizable, Impact Resistant, 400 Watt-Hour Secondary Battery 9-16-68.

TABLE II

FACTORS AND ASSUMPTIONS FOR DESIGN OF 25 AH NARROW PLATE CELL PACK

POSITIVE PLATE

Active Ag Density = 69.4 g/in^3
Formation Charge Efficiency = 82%
Discharge Efficiency = 0.30 AH/gAg

CORE STRUCTURE

.015 solid Inconel 600 sheet with 1 mil silver plate - both sides and 2/0 Ag grid - both sides.

OR

.017 Zirconium Sheet with 2/0 Ag grid - both sides

Core thickness allowance = 21 mils
Total Plate Width = 1.10"

NEGATIVE PLATE

Mix Density = 49 g/in^3
ZnO Formation Charge Efficiency = 95%
Mix Material = 91% ZnO, 7% HgS, 2% Teflon.

CORE STRUCTURE

0.010 solid silver sheet with 2/0 Distorted Ag grid - both sides.

OR

0.048 chemically milled Ag sheet with 65-70% open space

Core thickness allowance = 14 mils
Total Plate Width = 0.90"

CELL PACK

Active Plate Width = 0.90

Separator - 8 layers SWRI-GX with 2.7 mil wet thickness allowance and 1 layer E-1488 polypropylene absorber.

Excess formation charge capacity of ZnO over active Ag = 10%

CELL

Ratio of cell pack weight to total cell weight = 0.65

TABLE III

FORMATION CHARGE AND DISCHARGE 25 AH HIGH IMPACT CELLS BEFORE SHOCK TESTS

Test	Unit	Low Cell	Median n = 12	High Cell
1. Open Circuit Voltages	volts			
As Manufactured		-0.351	-0.009	+0.143
Before Heat Sterilization		+ .758	+ .765	+ .773
After Heat Sterilization (1)		+ .008	+ .010	+ .016
2. Formation Charge				
• First Stage Input 0.5A to 2.00V	AH	24.2	26.3	30.0
• Partial Discharge 2.0A to 1.70V	AH	4.0	5.2	6.0
• Recharge Input 0.5A to 2.00V	AH	14.9	18.7	22.2
• Net Input (all steps)	AH	37.4	39.8	42.4
	AH/gAg	.385	.410	.436
3. Pressure on Formation Charge (2)	psig (max)	5	32	46 (3)
4. Discharge Capacity				
• 12A to 1.25V	AH	28.4	31.8	35.6
• 2.4A to 1.25V	AH	1.6	2.6	3.3
• Both Steps (total)	AH	30.0	34.8	38.9
	AH/gAg	.308	.358	.400
5. Cycle 2 Recharge				
• 0.5A to 2.00V	AH	30.9	35.1	37.2

Notes:
(1) All cells heat sterilized wet sealed 72 hours at 135°C
(2) Cells gassed on formation charge, vented 16 hours, then resealed.
(3) Cell S/N 9 vented second time before discharge.

TABLE IV

EFFECT OF HIGH IMPACT ON PROTOTYPE 5 AH CELLS

S/N	Velocity Axis	Stopping Distance (in.)	Shock Duration (Msec.)	Mean "g" Load	Peak "g" Load	Loaded Voltage Drop, mv				Discharge Capacity AH		
						5A	10A	20A	30A	3.3A	0.7A	Total
10	+y (Terminals forward)	1.000	--	2,410	--	29	46	73	76	2.80	.52	3.32
7		0.755	1.0	3,050	3,600	29	45	67	180	3.30	.23	3.53(s)
12	-y (Terminals aft)	0.970	1.2	2,460	--	29	37	47	73	3.30	.07	3.37
17		0.785	--	3,115	--	23	31	40	57	2.80	.16	2.96
14	-X (+ Terminal edge forward)	1.035	1.5	2,380	--	31	47	71	68	2.80	.30	3.10
11		0.780	1.0	3,150	3,500	233	188	77	--	1.48	.50	1.98(s)

Summary of Mean Effects on Capacity Out at 3.3A Rate - AH

Axis	$\bar{X}$ (2 cells)	Shock Load	$\bar{X}$ (3 cells)
+y	3.05	2,400 "g"	2.97
-y	3.05	3,100 "g"	2.53
-X	2.14		

TABLE V

EFFECTS OF VARIOUS DESIGN MODIFICATIONS ON NON-IMPACT, HEAT STERILIZED CELLS

Group No.	Design Modification	Sample Size	Capacity (AH) Min.	$\bar{X}$	Max.	Test Cycles	Test Method
1	Control, PPO 531-801 Jar & Cover EM-476 Absorber, 1L SWRI-GX Membrane, 5L EM-476 Retainer, 1L RNF-100 Tubing on Leads	6	4.74	5.11	5.62	1	Formation Charge: 0.17 A. to 2.00 V. Partial Discharge - 1.5 AH Recharge: 0.17 A. to 2.00 V. Discharge: 3.3 A. to 1.30 V. then 0.7 A. to 1.30 V.
2	Added Exposure of Epoxy Surface						9 Cycles:
	o Epoxy DEN438EK85/DMP30, 2.8 in^2	3	4.43	5.20	6.31		Charge @ 0.25 A. to 1.97 V.
	o Epoxy DEN438EK85/DMP30, 1.1 in^2	3	4.68	5.02	5.75	1-9	Discharge @ 3.3 A. to
	o Epoxy Epocast 221/927 1.7 in^2	3	4.56	4.87	5.44		1.30 V. then 0.7 A. to
	o Epoxy Isochem 811B/811A 1.7 in^2	3	4.20	5.09	5.86		1.30 V.
	o No Epoxy - Controls	6	4.44	4.97	5.55		
3	Changes in Separator System						
	o Deleted EM-476 Absorber and retainer and added 1L SWRI-GX	4	5.33	5.91	6.95		
	o Deleted EM-476 Absorber and retainer, substituted 6L RAI-116 for 5L SWRI-GX	4	7.83	7.90	7.94	1	Same as Group #1
	● Deleted EM-476 Retainer only	6	6.99	7.52	8.05		
4	Change of Cell Case & Cover Material						16 Cycles:
	o PPO 531-801	4	3.26	4.90	7.94	1-16	Charge @ 0.25 A. to 1.97 V.
	o PPO 534-801	4	3.27	5.18	7.92		Discharge @ 3.3 A. to 1.30 V. then 0.7 A. to 1.30 V.
5	Deleted RNF-100 Tubing						
	o Group A	2	9.9	10.3	10.6	1	Same as Group #1
	● Group B	2	8.2	8.9	9.9	2-4	3 cycles same as Group 2.
6	Same as Group 5 Modification Except added 2 cc Epocast 221/927 platelock active Ag each cell = 29.2 g.	1		10.3			Same as Group #1.
7	Deleted RNF-100 Tubing	3	9.5	10.1	10.6	@Cycle 1	9 Cycles @ 100% depth
	No sandblasting of seal areas		8.6	9.6	10.6	@Cycle 49	Same as Group #4.
	No platelock		Shorted by Zinc Penetration			@Cycle 74	65-74 cycles @50% depth in 6-7 months wet Life (21 Hr. Chg./3 Hr. Dischg.)

TABLE VI
Physical Characteristics Heat Sterilizable Membranes

Test	Unit	SWRI-GX $\bar{X}$	SWRI-GX ± 3 s	RAI-116 $\bar{X}$	RAI-116 ± 3 s
1. Lots Tested	n	10	-	13	-
2. Thickness, Dry	mils	1.7	0.6 - 2.8	2.2	0.1 - 4.5
Wet	"	2.2	1.3 - 3.1	2.8	0.2 - 5.8
3. Weight, Dry	mg/in^2	22	15 - 29	25	14 - 36
Wet	"	50	40 - 59	58	30 - 86
4. Dimensional Change					
L (Roll)		+6	0-12	+5	-4 +13
W	%	+8	1-15	+4	-4 +12
T		+36	11-61	+32	-26 +89
5. Electrolyte Absorption	G/G	1.6	0.7 - 2.5	1.6	0.9 - 2.3
6. Porosity	%	60	39 - 81	57	15 - 100
7. Pore Diameter	A°	7.0	1.0-13.3	9.2	0.6-19.3

Test Method ESB-MS-263 (31% KOH)

TABLE VII

STRENGTH OF TREATED SILVER SHEET TENSILE SPECIMENS

Sample No.	Treatments Before Test	Force to Yield (Lbs.)	Force to Failure (Lbs.)	Yield Strength (ksi)	Ultimate Strength (4) (ksi)
1	Controls-Material as received	225	225	45	45
2		250	250	50	50
3	Heat Sterilized (1)	130	170	26	34
4		125	155	25	31
5		125	165	25	33
6	Mercury Amalgamation (2)	260	260	52	52
7		245	245	49	49
8	Mercury Amalgamation and Heat Sterilized	125	170	25	34
9		125	170	25	34
10		125	170	25	34
11	Mercury Amalgamation plus Sintered (3) plus Heat Sterilized	70	150	14	30
12		70	120	14	24

NOTES:

(1) All heat sterilization at 275°F for 72 hours.
(2) Amount of amalgamation = 0.0001 inch thick layer.
(3) Sintered dry in oven at 325°C for 1 hour
(4) Ultimate strength based on original cross-section

TABLE VIII

FORMATION CHARGE AND DISCHARGE 5.0 AH HIGH IMPACT CELLS
BEFORE SHOCK TESTS

Test	Unit	Low Cell	Median n = 12	High Cell
1. Open Circuit Voltages	volts			
As Manufactured		-0.193	-0.100	+0.107
Before Heat Sterilization		+0.731	+0.750	+0.760
After Heat Sterilization(1)		-0.002	+0.005	+0.016
2. Formation Charge	AH			
• First Stage Input 0.15A to 2.00V		4.34	5.81	6.60
• Partial Discharge 0.4A to 1.70V		0.85	1.17	1.20
• Recharge Input 0.15A to 2.00V		2.00	2.50	3.26
• Net Input, (all steps)	AH	6.55	7.27	7.68
	AH/gAg	.31	.35	.37
3. Discharge Capacity	AH			
• 3.2A to 1.25V	AH	5.12(2)	5.60	5.76
• 0.65A to 1.25V	AH	.34	.52	.70
• Total Both Rates	AH	5.46	6.12	6.46
	AH/g	.26	.29	.31

Notes: (1) After 72 hours at 135°C
(2) Developed leak case to cover between recharge and discharge.

TABLE IX

FOUR CYCLE TEST ON 5 AH HIGH IMPACT CELL

	Charge		Discharge			Efficiency
Cycle No.	Current Amps	Capacity AH	Current Amps	Capacity AH	Voltage Volts	AH/ gAg
1	0.15	7.27 (1)	3.20 0.65	5.55 0.62 6.17		0.26 0.03 0.29
2	0.20	6.14	3.20	3.20 (2)		0.15
3	0.20	4.40	4.6 1.0	4.50 0.60 5.10		0.21 0.03 0.24
4	0.20	4.90	4.6	3.68		0.17
5	0.15	4.35 (1)	4.6	3.90		0.19
6	0.15	4.04				

NOTES: (1) Cycles 1 and 5 charges included partial discharge - recharge.

(2) 30 day charged stand test.

(3) Test end voltages: 2.00 volts on charge, 1.25 volts on discharge.

TABLE X

DEVELOPMENT OBJECTIVES VS ACCOMPLISHMENT
5 AH HEAT STERILIZABLE HIGH IMPACT CELLS

	Design or Operating Parameter	Unit	Objective (1)	Accomplishment
1.	Energy Storage	WHr	80	76 (6.3 WHr/cell)
2.	Shelf Life before Use	Years	1	--
3.	Mission Environment			
	Heat Sterilization at 135°C	Hours	72	72
	Space Travel	Months	9	--
	Landing Shock & Velocity	g	4,000	up to 4,000
		ft/sec.	120	up to 120
	Operating Temperature	°C	+10 to +55	25
4.	Discharge Wattage (12 cells)	Watts	80	78 (6.5 watts/cell)
5.	Voltage (12 cells)	Volts	14.5 to 22.5	
6.	Capacity at 4.6A to 1.20 V	AH	4.7	4.5
7.	Cell Voltage at Rated Wattage	Volts	--	1.41
8.	Cycle Life, 100%, 80 Watts	Each	4	4 but less than 100% rated output
9.	Charging Time, max.	Hours	72	30-50
10.	Cell Dimensions and Volume			
	L	in.	--	1.13
	W	in.	--	1.97
	H (over jar)	in.	--	3.36
	Volume	in^3	--	7.48
11.	Cell Weight	lb.	--	0.60
12.	Energy Density	WHr/lb.	15	10.6 (cell only)
		WHr/in^3	--	0.9

(1) JPL Engineering Memorandum 342-70 Design Goals Power Subsystem Heat Sterilizable, Impact Resistant, 80 Watt Hour Battery, 9-16-68.

TABLE XI

DISCHARGE VOLTAGE-ENERGY CHARACTERISTICS,
MODEL 364 CELLS
NOMINAL ENERGY REQUIREMENTS= 111 WH

Discharge Cycle	Non-Sterile Sample Size = 3			Heat Sterilized Sample Size = 5		
	$\bar{X}_3$	Range Min.	Range Max.	$\bar{X}_5$	Range Min.	Range Max.
Formation						
Voltage, initial (V)	1.56	1.54	1.58	1.61	1.55	1.68
plateau (V)	1.45	1.445	1.455	1.445	1.435	1.45
average (V)	1.439	1.436	1.446	1.443	1.427	1.461
Energy, (WH)	146.5	134.2	153.6	139.3	130.4	147.3
Energy density (WH/lb)	57.9	53.0	60.7	55.1	51.5	58.3
Cycle No. 1						
Voltage, initial (V)	1.79	1.78	1.795	1.77	1.77	1.78
plateau (V)	1.49	1.46	1.48	1.47	1.46	1.48
average (V)	1.507	1.498	1.517	1.501	1.489	1.529
Energy (WH)	130.0	129.1	130.9	131.9	122.3	138.0
Energy density (WH/lb)	51.2	51.0	51.6	52.0	48.4	54.5
Cycle No. 2						
Voltage, initial (V)	1.778	1.775	1.780	1.783	1.765	1.795
plateau (V)	1.465	1.460	1.470	1.464	1.450	1.480
average (V)	1.496	1.487	1.503	1.507	1.485	1.525
Energy (WH)	136.1	135.3	137.8	127.2	113.8	133.6
Energy density (WH/lb)	53.9	53.5	54.4	50.3	44.9	52.8
Cycle No. 3						
Voltage, initial (V)	1.768	1.762	1.776	1.769	1.634	1.790
plateau (V)	1.480	1.476	1.488	1.484	1.465	1.500
average (V)	1.513	1.500	1.527	1.520	1.488	1.539
Energy (WH)	129.4	123.9	136.8	132.8	109.8	156.8
Energy density (WH/lb)	51.2	49.0	54.0	51.6	43.4	61.9

NOTES: (1) Heat sterilization 120 hours at 135°C in N_2.
(2) Cell discharges: 20 amps to 1.25 V (108 ma/in^2).

TABLE XII

PROTOTYPE 70 AH CELL DESIGN

Design Parameter	Unit	Previous Design	New Design
1. Capacity, rated @ C/4	AH	80	70
2. Plates/cell	+/-/-1/2	9/8/2	Same
3. Active material/cell,			
Positive	g Ag	286	248
Negative	g ZnO	198	187
4. ZnO: Ag ratio, wt.		0.69:1	0.75:1
5. Active area/cell	in^2	186	164
6. Plate grid type and weight	die and g/in^2	2/0 - 0.448 expanded interrupted	3/0 - .224 expanded, double with 0.010" Ag channel frame.
7. Positive process	type	Sintered Ag	Same
8. Negative process and composition active material: ZnO, HgS, teflon	type	Pressed powder 91-7-2	Sintered teflonated 91-4-5
9. Plate thickness and weight	mils/g		
• Positive		48 / 43.7	43 / 42.4
• Center negative		56 / 33.0	55 / 37.0
• End negative		33 / 20.9	29 / 25.6
10. Separation SWRI-GX			
• Negative retainer	No. layers	1	None
• Negative wrap	No. layers	6	9
• Wet thk. W & W/O overlap	Mils	2.33 / 2.48	2.26 / 2.40
11. Jar height (PPO 534-801)	in.	4.82	4.92
12. Cover (PPO 534-801	type	Machined	Molded
13. Weight sealed cells	lb.	2.53	2.74

TABLE XIII

INITIAL CYCLE TESTS ON 70 AH RELIABILITY CELLS (AFTER HEAT STERILIZATION)

Test Event	Unit	Minimum	Mean	Maximum
Preformation Charge				
Theoretical	AH		1.93	
Actual	AH	1.81	1.99	2.00
Terminal Voltage	Volts	1.592	1.596	1.606
Formation Charge (0.9A to 1.97 V/C)	AH	88.8	95.6	109.0
Maximum Pressure	Psig	4	28	60
Cycle 1 Discharge (17.5A to 1.25 V/C)	AH	72.8	88.7	100.
Cycle 2 Charge (1.5A then 0.9A to 2.02 V/C)	AH	71.1	79.0	89.8
Partial Discharge (2.0A for 8.1 Hrs)	AH	16.2	16.2	16.2
Recharge as above	AH	30.1	34.8	40.5
Net Input	AH	90.9	97.6	105.
Cycle 2 Discharge (17.5A to 1.25 V/C)	AH	91.5	97.5	103.
Discharge Time	Hours		5.6	
Cell Weight	Lb.		2.74	
Cell Volume	in^3		40.6	
Energy Output	WHr.		146	
Energy Density	WH/lb.		53	
	WH/in^3		3.7	

TABLE XIV

PERFORMANCE OF 70 AH CELLS ON CHARGED STAND AT 72°F

Stand Time (Days)	Parameter	Units	Cell Serial Numbers			
			28	37	25	28
0	Open circuit voltage	Volts	1.855	1.855	1.855	1.855
13	Open circuit voltage	Volts	1.858	1.858	1.858	1.858
	Pressure	In. Hg	-18		-12	-20
19	Open circuit voltage	Volts	1.861	1.861	1.861	1.862
	Pressure	In. Hg	-17		-12	-20
31	Open circuit voltage	Volts	1.855	1.859	1.860	1.861
	Pressure	In. Hg	-15	-13	-13	-21

TABLE XV

PERFORMANCE OF 70 AH CELLS ON DISCHARGE STAND @ 72°F

Stand Time (Days)	Parameter	Units	Cell Serial Number								
			20	39	30	32	34	19	23	26	35
0	Open circuit voltage	Volts	0.48	0.48	0.46	0.48	0.46	0.46	0.48	0.48	0.46
6	Open circuit voltage	Volts	0.39	0.38	0.38	0.38	0.37	0.38	0.47	0.48	0.37
19	Open circuit voltage Pressure	Volts Psig	0.37 7	0.36	0.37 8	0.36 7	0.36	0.38 3	0.36 8	0.27	0.36 8
25	Open circuit voltage Pressure	Volts Psig	0.37 7.	0.36	0.37 9	0.36 9	0.36	0.38 3	0.36 10	0.28	0.36 10
31	Open circuit voltage Pressure	Volts Psig	0.36 9.5	0.36	0.37 9	0.36 11	0.36	0.38 4	0.36 13	0.27	0.36 12

NOTE: Cells S/N 26, 34, and 39 have no pressure gage.

TABLE XVI

PERFORMANCE OF 70 AH CELLS ON FLOAT CHARGE AT 72°F

Parameters	Cell Serial Numbers									Current (Milliamps)
	41	22	45	44	29	43	40	24	42	
Cell Voltages (Volts)										
• Open Circuit	1.86	1.855	1.86	1.855	1.855	1.86	1.855	1.855	1.86	
• At Beginning of Charge	1.87	1.87	1.87	1.87	1.87	1.87	1.87	1.87	1.87	500
• After 45 minutes										160
113 minutes										100
198 minutes										60
4.5 hours										50
7.8 hours										50
8.5 hours										50
9.5 hours										45
4 days	1.87	1.88	1.88	1.87	1.87	1.87	1.90	1.87	1.87	14
13 days	1.868	1.922	1.884	1.868	1.869	1.868	1.870	1.868	1.868	6-9
19 days	1.863	1.930	1.932	1.863	1.863	1.863	1.926	1.863	1.863	11-14
25 days	1.862	1.860	1.862	1.863	1.861	1.862	1.923	1.861	1.866	6-14
Cell Pressures (psig) (2)										
• After 13 days	8.0		5.5	-2.5		0	0		-7.5	-
19 days	8.0		31	-2.5		-2	-2.5		-8.0	-
25 days	5.5		10	-3.0		-2.5	-2.5		-8.0	-

(1) Float charge at C. P. of 9 x 1.87 = 16.83 ± 0.09 volts in series array.

(2) Cells S/N 22, 24, and 29 have no pressure gage.

TABLE XVII

OBJECTIVES VS ACCOMPLISHMENTS 70 AH HEAT STERILIZABLE CELLS

	Design or Operating Parameter	Unit	Objectives (1)	Observed
1.	Energy Storage, Rated	WHr.	1200	
	Delivered (12 Cells)	"		1750
2.	Energy Density, Battery	WH/lb.	35	42 (est.)
3.	Energy Density, Cells	WH/lb.		53
4.	Voltage Regulation at 300 W Load	Volts/12 cell	14.5-22.5	
		Volts/Cell	1.21-1.87	1.25-1.87
5.	Cycle Life, 100% C	ea.	4	16+
6.	Charge Time to 100% C	Hrs.	72 (max.)	51 (2)
7.	Operating Temperature	°C	10 to 55	20-30 Tested
8.	Storage Life			
	Prelaunch, 0 to 25°C	Yr.	1	NT
	Transit, -10 to 25°C	Mos.	9	NT
9.	Wet Life to Short in Charged State	Mos.	10	16
10.	Heat Sterilization at 135 ±2°C	Hrs.	74	72+
	in Nitrogen in Discharged State Sealed			
11.	Shock - Launch & Transit	g	250	NT
	3 axis, 2 directions, 30 shocks	Msec.	0.7 ±.2	NT
12.	Vibration - Entry & Landing			
	Sine 100 to 2000 Hz	Grms.	35	32
	Random 20 to 2000 Hz	Grms.	25	25
13.	Deceleration, Entry, 20 secs.	g	250	NT

(1) JPL Engineering Memorandum 342-71 Heat Sterilizable 1200 Watt Hour Battery.

(2) Any cycle except formation cycle.

TABLE XVIII

OBJECTIVES VS ACCOMPLISHMENTS
25 AH INTERMEDIATE CYCLE LIFE CELL

Design or Test Parameter	Unit	Specification Requirement (1)	Accomplishment: Model 379 Cell	Accomplishment: 12-Cell Battery (Est.)
1. Battery Energy (12 Cells)	WH	400	48	575
2. Energy Density, Minimum	WH/lb	20	44	40
3. Voltage, Load (12 Cells), 8A	Volts	14.5-22.5	1.50	18
4. Capacity	AH	25	32	32
5. Wattage (12 Cells), 16A	W	200	24	284
6. Cycle Life, 50% Depth	ea.	90	168	NT
7. Charge Time, max. 100%	hrs.	72	60	NT
8. Cycle	hrs.			
Charge		10	10	
Discharge		14	2	
9. Operating Temperature	°C	10-55	25	
10. Storage Life				
Prelaunch, 0 to 25°C	mos.	12	12 (Uncharged)	
In Transit, -10 to 25°C	mos.	9	9.5 (Charged)	
11. Environment	Torr.	10^{-12} to 800	Ambient	
12. Heat Sterilization	ea.	3 24.5 hrs @ 135°C	120 hours @ 135°C	
13. Shock-Launch and Transit	ea.	30 250g, 0.7 ±0.2 msec	Cells at JPL for tests	
14. Vibration-Entry & Landing	g Hz	30 16 to 2000	Cells at JPL for tests	
15. Deceleration - Entry	g secs.	250 30	Cells at JPL for tests	
16. Cell Weight	lb.		1.08	

(1) JPL Engineering Memorandum 342-68.

TABLE XIX

EPOXY BUTT JOINT STRENGTHS WITH PPO 534-801

Epoxy System (Mix Ratio)	No Sterilization				Sterilized 72 hrs. @ 135°C			
	Force to Break (lbs)	Area of Break (in^2)	Tensile Strength (psi)	Mean Strength (psi)	Force to Break (lbs)	Area to Break (in^2)	Tensile Strength (psi)	Mean Strength (psi)
31B/9216 (100:10)	150 210 170 180 205	.059 .059 .058 .057 .057	2530 3580 2940 3160 3610	3160	120 160 120 120	.058 .057 .057 .058	2055 2793 2094 2058	2250
31A/9216 (100:19)	80 130 105 130 100	.058 .058 .059 .059 .059	1370 2230 1770 2210 1700	1860	30 100 20 40 90	.059 .057 .059 .058 .059	510 1751 341 694 1538	970
DEN438EK85/ DMP30 (100:3)	110 290 215 110 190	.057 .058 .057 .058 .058	1920 4990 3750 1900 3250	3160	290 260 215 140 40	.058 .058 .057 .058 .059	5026 4460 3759 2393 678	3260
DEN438EK85/ DMP 30 (100:5)	240 120 125 125 140	.058 .058 .058 .057 .057	4130 2060 2160 2180 2440	2590	170 235 130 100 170	.058 .059 .058 .058 .058	2941 4003 2250 1712 2946	2770

NOTES:

- Cure - 24-36 hours @ room temperature + 32 hours @ 212°F in M40 KOH in a sealed bomb.

TABLE XX

LOW IMPACT 25 AH CELL CYCLING TEST

Cell Design Variables						Number of Cycles, DOD					
Plate Wrap	Separation L/Type	Negative Density g/in^3	Electrolyte Weight g***	Electrolyte Weight g/gAg	C Rating AH	100% Single Step	50% Single Step	50% Two Step Discharge	Total Cycles	Capacity-Accumulated Output All Cycles AH	Output Energy** On DAS Per Auto-Cycle W-Hr.
+	1L Pellon 2530 W 7L GX	49	123	1.40	22	5	36 (11.4AH)*	127 127 125	168 FS 168 166	1920 1920 1900	16.6
+	same	42	124	1.55	20	5	36 (9.8AH)	123 123 77	164 FS 164 118FS	1690 1690 1220	15.4
+	9L GX only	42	125	1.56	20	5	30 (9.7AH)	106 106 56-	141 141 91	1480 1480 960	14.9
-	same	42	124	1.29	24	5	30 (11.8AH)	69 92 49	104FS 127 84	1270 1550 1040	17.6
-	same	49	118	1.13	26	5	28 (12.2AH)	77 45 45	110 78 78FS	1440 1030 1030	19.3

* Discharge capacity per cycle at C/4 rate
** Includes energy of both discharge steps
*** 43% containing 114 g ZnO per liter.

FS = Failure by short.

TABLE XXI

STERILE VS NON-STERILE DISCHARGE CAPACITIES
25 AH CELLS - FIRST THREE CYCLES

Design Parameter

Plate Wrap	Separator System	Negative Plate Density g/in^3	Electrolyte Per Cell gm	(1) Cycle	Non-Sterile Input	Non-Sterile Output	Sterile (*) Input	Sterile (*) Output
+	1L Pellon 2530W and 7L GX	49	123	1	34.5	33.6	34.2	31.6
				2	32.4	30.6	28.9	26.9
				3	26.5	27.5	26.5	27.5
				Net	1.7		3.6	
+	Same	42	124	1	37.5	36.0	37.4	33.4
				2	32.8	30.9	29.9	29.6
				3	29.1	29.9	27.5	28.1
				Net	2.6		3.7	
+	9L GX No absorber	42	125	1	35.4	34.4	34.7	31.8
				2	29.7	28.0	28.9	26.4
				3	31.1	29.7	26.8	27.1
				Net			5.1	
-	Same	42	124	1	37.4	36.6	38.0	35.6
				2	34.2	32.2	31.9	29.3
				3	33.5	32.6	31.6	33.0
				Net	3.7		3.6	
-	Same	49	118	1	44.3	43.5	41.2	37.2
				2	36.9	34.1	38.1	35.0
				3	41.8	43.4	35.4	41.8
				Net	2.0		0.7	

NOTES: (1) Cycle 1 - 8.0A; Cycle 2 - 2.0A; Cycle 3 - 16A to 1.30 V.

(*) 72 hours 135°C in N_2.

TABLE XXII

EFFECT OF CYCLING BEFORE HEAT STERILIZATION

Cell Design Type	Sterile Pre-Test Cell Discharge Capacities (Amp-Hr)			Discharge Efficiencies (1) (Amp-Hr/g Ag)		
				Pre-Test Cells		
	8 Amp	16 Amp	2 Amp	Pre-Sterilization	Post-Sterilization	Cells Not Pre-Tested
1	28.3	29.9	28.5	0.342	0.326	0.322
						0.323
2	32.5	31.4	30.5	0.399	0.389	0.347
						0.395
						0.376
3	32.2	29.1	27.4	0.374	0.360	0.368
						0.344
						0.346
4	32.0	33.3	30.6	0.357	0.338	0.357
						0.344
5	30.4	39.9	27.5	0.389	0.314	0.351
						0.366
						0.373
All Types	--	--	--	0.372	0.345	0.352

(1) Average over 3 discharges.

TABLE XXIII

CYCLE LIFE OF PRETEST CELL GROUP

Design Group	Design Factors: Plate Wrap	Separator System	Negative Plate Density g/in^3	Capacity C Rating AH	Number of Cycles: 100% Depth	Two-Step Dischargers	Total Cycles	Accumulated Capacity AH
(-1)	+	1L Pellon 2530W and 7L GX	49	22	9	88 FC	97	1244
(-2)	+	Same	42	20	9	98 FS	107	1263
(-3)	+	9L GX No absorber	42	20	9	83 FC	92	1113
(-4)	-	Same	42	24	9	69 FC	78	1102
(-5)	-	Same	49	26	9	51 NF	60	970

Wet Life: 5.5 months from activation.

FS = Failure by short.

FC = Capacity failure.

NF = No failure.

TABLE XXIV

EFFECT OF PLATELOCK ON DISCHARGE EFFICIENCY
MODEL 379 25 AH CELLS

Design Wrap	Negative Density (g/in^3)	Mean Discharge Efficiency (Amp-Hr/g Ag)* No Platelock	Mean Discharge Efficiency (Amp-Hr/g Ag)* Platelock	Response
(+)	45	0.322 0.323	0.262	-18.6%
(+)	42	0.347 0.395 0.376	0.368	-1.3%
(+)	42	0.368 0.344 0.346	0.320	-9.4%
(-)	42	0.357 0.344	0.293	-16.3%
(-)	45	0.351 0.366 0.373	0.257	-29.2%
All Types		$\bar{X}_1 = .352$	$\bar{X}_2 = .300$	-14.8%

(*) Mean of 3 cycles at discharge rates 8A, 16A, and 2A to 1.25 volts.

TABLE XXV

LIFE HISTORY OF 25 AH PLATE-LOCK CELL GROUP
(PRIOR TO ENVIRONMENTAL TESTS)

Test or Design Parameter	Unit	Observation by Cell S/N				
		21	22	23	24	25
1. Preformation Charge	AH	.67	.67	.67	.81	.81
2. Heat Sterilization 100 hours at 135°C		X	X	X	X	X
3. Formation Charge	AH	25.5	31.8	38.3	26.8	31.8
• Partial Discharge	AH	7.9	8.4	6.9	7.9	9.8
• Recharge	AH	12.6	14.1	10.4	14.5	15.4
• Net Input	AH	30.2	37.5	39.8	35.4	37.4
4. Formation Discharge 8A to 1.25V	AH	26.6	35.0	30.6	32.6	28.8
5. Cycle 2 Charge 1A to 2.03V	AH	23.6	28.3	23.6	26.6	28.3
6. Cycle 2 Discharge 16A to 1.25V	AH	22.0	30.1	28.8	24.0	27.5
Midvoltage	volts	1.44	1.44	1.43	1.47	1.44
7. Cycle 3 Charge 1A to 2.03V	AH	23.0	28.4	23.8	26.6	25.5
8. Cycle 3 Discharge 2A to 1.25V	AH	21.2	24.2	22.4	24.2	24.2
Midvoltage	volts	1.52	1.50	1.49	1.50	1.51
9. Cycle 4 Charge 1A to 2.03V	AH	25.9	26.7	26.7	23.1	26.3
10. Net Input, All Cycles	AH	32.9	31.6	32.1	30.9	37.6
11. Charged Stand at JPL	mos.	7.5	7.5	7.5	7.5	7.5
12. Cycle 4 Discharge	AH					
Step 1. 8A to 1.25V		19.3	23.3	20.9	20.5	22.1
Step 2. 2A to 1.25V		1.1	.9	.5	1.6	7.2
Total Output	AH	20.4	24.2	21.4	22.1	29.3

TABLE XXV (Continued)

LIFE HISTORY OF 25 AH PLATE-LOCK CELL GROUP
(PRIOR TO ENVIRONMENTAL TESTS)

Test or Design Parameter	Unit	Observation by Cell S/N				
		21	22	23	24	25
13. Capacity Loss in 7.5 Months	AH	0.8	0	1.0	2.1	-5.1
% Loss vs Item 8	%	3.8	0	4.5	8.7	-
14. Capacity Loss in 9.0 Months	AH	7.3	11.7	9.7	12.1	6.7
% Loss vs Item 4	%	27.4	33.4	31.6	37.1	23.2
15. Cycle 5 Charge	AH	21.9	24.0	20.0	23.1	28.9
• Partial Discharge	AH	5.0	5.0	5.0	5.0	5.0
• Recharge Input	AH	11.7	11.4	8.7	7.6	8.8
• Net Input	AH	28.6	30.4	23.7	25.7	32.7
16. Cycle 5 Discharge						
Step 1. 8A to 1.25V	AH	26.0	27.2	23.2	24.9	25.7
Step 2. 2A to 1.25V	AH	.9	1.2	.8	1.9	2.6
Net Output, both steps	AH	26.9	28.4	24.0	26.8	28.3
17. Cycle 6 Charge	AH	27.8	28.0	18.8	26.8	27.2
• Partial Discharge	AH	5.0	5.0	3.0	5.0	5.0
• Recharge	AH	9.6	9.4	7.2	6.5	6.0
• Net Input	AH	32.4	32.4	22.9	28.3	28.2
18. Silver Active Weight Per Cell	g	88.7	80.9	82.2	94.5	103.7
19. Rated Capacity	AH	22	20	21	24	25
20. Separator System						
• Pellon 2530W		1L	1L	-	-	-
• SWRI-GX		7L	7L	9L	9L	9L
• Wrap		+	+	+	-	-
21. Negative Plate Density	g/in^3	49	42	42	42	49

TABLE XXVI

DESIGN AND PERFORMANCE FEATURES OF
CELL DESIGNS USED IN HIGH CYCLE LIFE DEVELOPMENT

Design Feature and Performance Attribute	Unit	Cell Characteristics: Engr. Design Model 172	Advanced Design Model 172	Best Final Design Model 389
1. Cell Dimensions				
o Length	in.	1.19	1.19	1.19
o Width	in.	3.35	3.35	3.35
o Height (over cover)	in.	4.74	4.74	5.32
2. Cell Volume	$in.^3$	18.9	18.9	21.2
3. Cell Weight, Wet	lb.	1.03	1.08	1.29
4. Case Material, PPO	Type	531-801	531-801	534-801
5. Positive Plate				
o Number	Each	6	6	4
o Width X Height	in.	2.56 X 3.12	2.56 X 3.12	2.63 X 3.75
o Thickness	in.	.031	.031	.028
o Active Silver/Plate	g.	16.1	16.1	17.8
o Active Area, Cell	$in.^3$	96	96	79
6. Negative Plate	Type	Pressed Powder	Pressed & Sintered	Pressed & Sintered
o Number	Each	7	7	5
o Width X Height	in.	2.56 X 3.12	2.56 X 3.12	2.83 X 3.88
o Thickness	in.		.047	.068
o Active Zinc Oxide	g.	11.4	15.4	29.8
o Grid Type (No. per Plate)		2/0 (1)	3/0 (2)	3/0 (2)
o Grid Weight/Area	$g/in.^2$	.20	.48	.48
7. Separator System				
o Absorber, Positive	Type	1L Pellon 2530W or None	None	1L Pellon 2140
o Membrane	Type	5L-GX	6L-GX	8L-GX
o Retainer, Negative	Type	1L-GX	None	None
o Plates Wrapped		Positive	Positive	Positive
8. Electrolyte	Type	M40-67 cc	M40-67 cc	M40-83 cc
9. Capacity, Rated	AH	27	27	20
10. Discharge Time	hr.	4.3	4.6	3.3
11. Discharge Rate	amp	8.0	8.0	8.0
12. Plateau Voltage	Volts	1.47	1.51	1.46
13. Energy	WH	50	56	38
14. Energy Density	WH/lb.	49	52	30
	$WH/in.^3$	2.65	2.96	1.80

TABLE XXVII

CELL DESIGN VARIABLES AND ASSIGNED COMBINATIONS
FOR CYCLE LIFE STUDY

CELL DESIGN VARIABLES

Variable	Factor Code Level		
	-1	0	1
A. Weight percent Teflon 7	5	7	9
B. Separator Wet Thickness Allowance (mils)	2.0	2.4	2.8
C. Zinc Oxide to Silver Weight Ratio	.9	1.2	1.5
D. Electrolyte Concentration Before Saturation (%)	41	43	45

VARIABLE COMBINATIONS

Cell No.	Variable and Level				Cell No.	Variable and Level			
	A	B	C	D		A	B	C	D
1	-1	-1	-1	-1	15	1	1	0	0
2	0	1	0	1	16	-1	0	0	0
3	1	0	1	0	17	0	-1	1	-1
4	-1	-1	1	0	18	1	1	-1	1
5	0	1	-1	-1	19	-1	1	-1	0
6	1	0	0	1	20	0	0	0	-1
7	-1	-1	0	1	21	1	-1	1	1
8	0	1	1	0	22	-1	1	1	1
9	1	0	-1	-1	23	0	0	-1	0
10	-1	0	-1	1	24	1	-1	0	-1
11	0	-1	0	0	25	-1	1	0	-1
12	1	1	1	-1	26	0	0	1	1
13	-1	0	1	-1	27	1	-1	-1	0
14	0	-1	-1	1					

TABLE XXVIII

MEAN 20 AH CELL DISCHARGE PERFORMANCE ON
100% DEPTH INITIAL CYCLES

Absorber Type	Absorber Wet Thickness Mils	Capacity (AH), Voltage (Volts), Efficiency (AH/gAg), and Residual Capacity Extended (E) vs Non-Extended Negatives (NE), Number Layers GX, Wrap Type						RATE	CODE
		7L	8L	10L					
		+	+	+	+	+	—		
		E	E	NE	E	E and Wedge	NE	Amp	
Kendall E-1488	8			(-2) (6)	(-4) (3)	(-6) (2)	(-1) (5)		
				26.1	26.6	26.8	27.1	8	C
				1.418	1.444	1.423	1.436		V
				0.366	0.374	0.377	0.381		E
4 mil each layer				22.7	23.0	24.6	22.6	16	C
				1.350	1.371	1.360	1.376		V
				0.319	0.323	0.346	0.318		E
				3.3	2.7	0.5	5.1		RC
	24	(-3) (7) Spiral Wrap							
		25.9						8	C
		1.410							V
		0.363							E
		23.6						16	C
		1.339							V
		0.333							E
		3.7							RC
Pellon 2140 one layer	11		(-7) (1)		(-5) (4)				
			26.6		26.5			8	C
			1.458		1.433				V
			0.374		0.363				E
			24.2		24.3			16	C
			1.407		1.378				V
			0.340		0.342				E
			-0.2		5.1				RC

Note: Design No. ( ) ( ) Performance Rank

Code: C = discharge capacity - AH
V = flat voltage - volts
E = silver utilization - AH/g
RC = residual capacity - AH

TABLE XXIX

400 CYCLE TEST ON 20 AH CELLS

REGIME A

20 2/3 Hours Charge - 3 1/3 Hours Discharge

Absorber Type	No. of Layers	Cell Cycle Life to 1.20 Volts by Serial Number				
		Number of Layers GX Separator and Wrap				
		7	8	10	10	10
		(+)	(+)	(+)	(+)	(-)
Kendall E1488I	2			2/ 11 - NF 12 - 149 13 - NF 14 - 142 15 - 179	4/ 26 - 179 27 - NF 28 - NF 29 - NF 30 - 220	1/ 1 - NF 2 - 156 3 - NF 4 - 153 5 - 183
	2				6/W 41 - NF 42 - 233 43 - 208 44 - NF 45 - NF	
	6	3/ 21 - 155 22 - 141 23 - 181 24 - NF 25 - NF				
Pellon 2140	1		7/ 51 - 241 52 - NF 53 - NF 54 - 243 55 - NF		5/ 31 - NF 32 - 162 33 - 188 34 - 179 35 - NF	
Other Code		E	E	NE	E	NE
Mean Cycle Life		159	240	157	4/ 199	164
					6W/220	
					5/ 176	

E = Extended negatives.
NE = Non-extended negatives (same L X W as positive).
W = Wedge shaped negatives.

n/ Indicates design type.

NF = no failure.

TABLE XXX

400 CYCLE TEST ON 20 AH CELLS
REGIME B

10 Hours Charge/14 Hours Discharge

Absorber Type	No. of Layers	Cell Cycle Life to 1.20 Volts by Serial Number			
		Number of Layers GX Separator and Wrap			
		8	10	10	10
		(+)	(+)	(+)	(-)
Kendall E1488I	2		2/ 16 - NF 17 - 159 18 - 123 19 - 107 20 - NF	6W/ 46 - 191 47 - NF 48 - NT 49 - NT 50 - 191	1/ 6 - 184 7 - 182 8 - 184 9 - 159 10 - NF
Pellon 2140	1	7/ 56 - NF 57 - 222 58 - 230 59 - NF 60 - 202		5/ 36 - NF 37 - NF 38 - NF 39 - NF 40 - NF 230 cycles completed	
Other Code		E	NE	E	NE
Mean Cycle Life		218	130	6W/191 5/ 239	175

E = Extended negatives

NE = Non-extended negatives (same L X W as positive).

W = Wedge shaped negatives.

n/ Indicates design type.

NF = no failure.

NT = no test.

FIGURE 1

SELECTION CRITERIA FOR PLATE WIDTH AND CORE THICKNESS

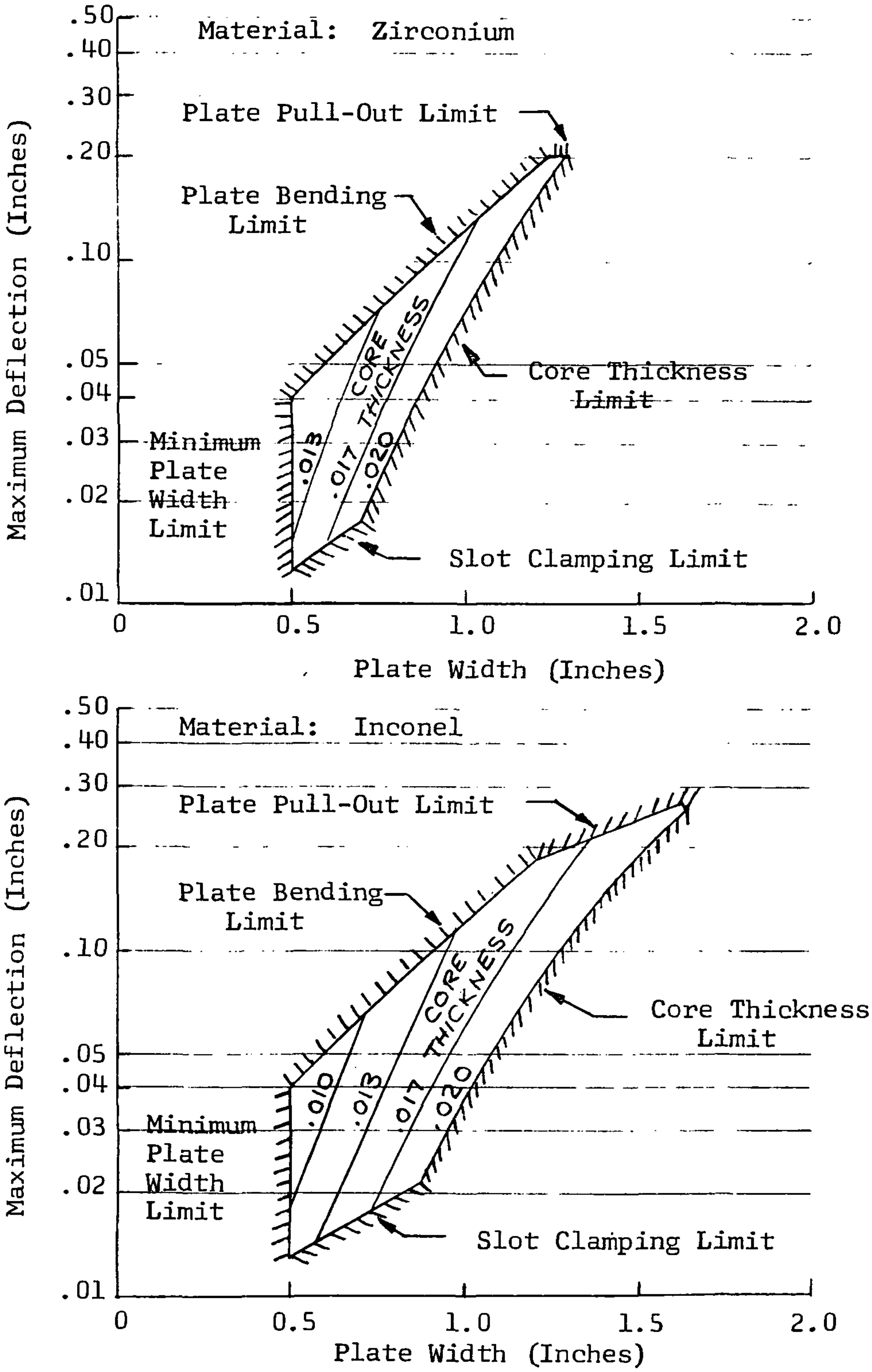


FIGURE 2

BUCKLING ANALYSIS FOR 1" WIDE PLATE
IN EDGEWISE SHOCK
3000 "G"

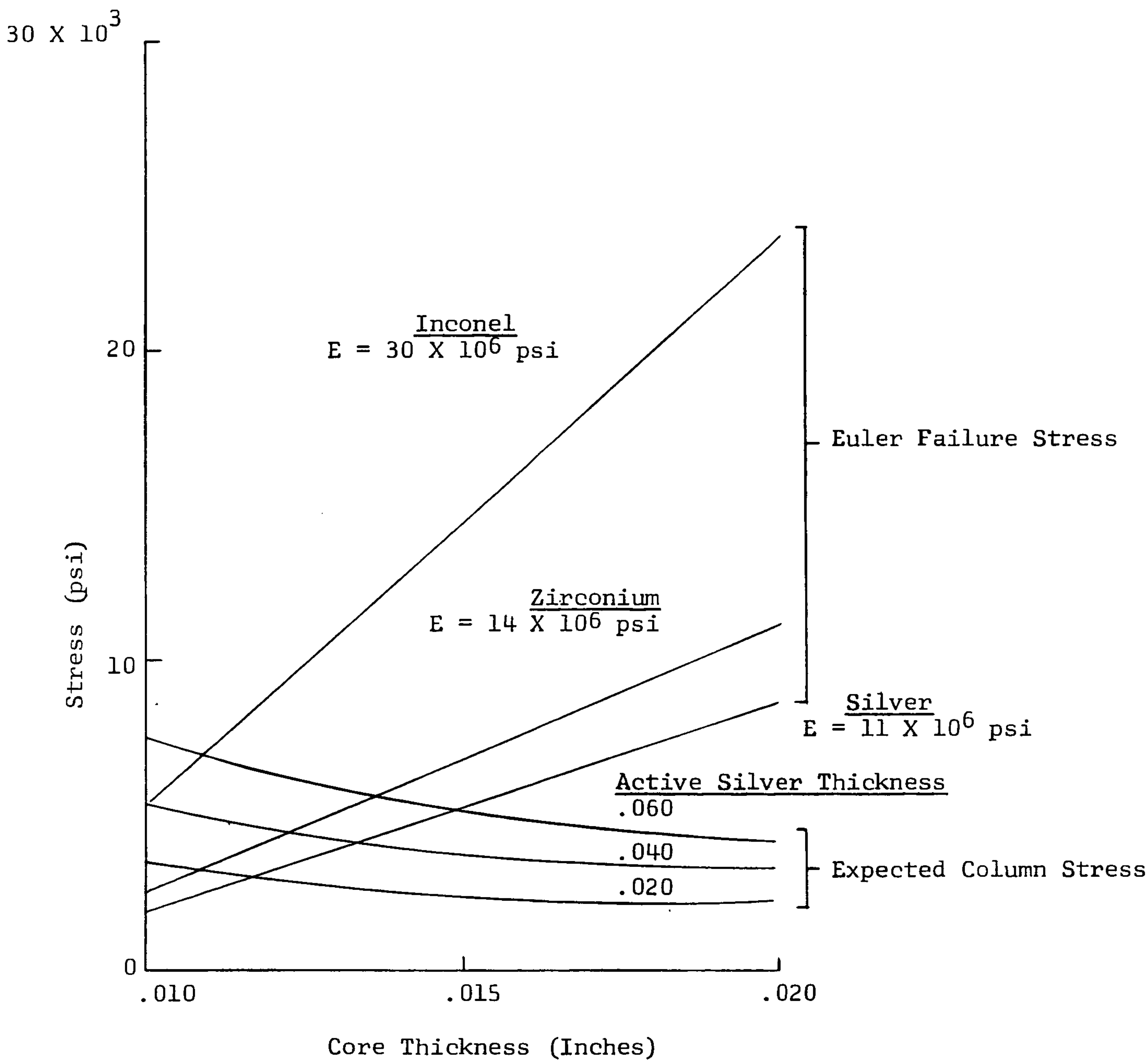


FIGURE 3

ELECTROCHEMICAL DESIGN PARAMETERS - NARROW PLATE 25 AH DESIGN

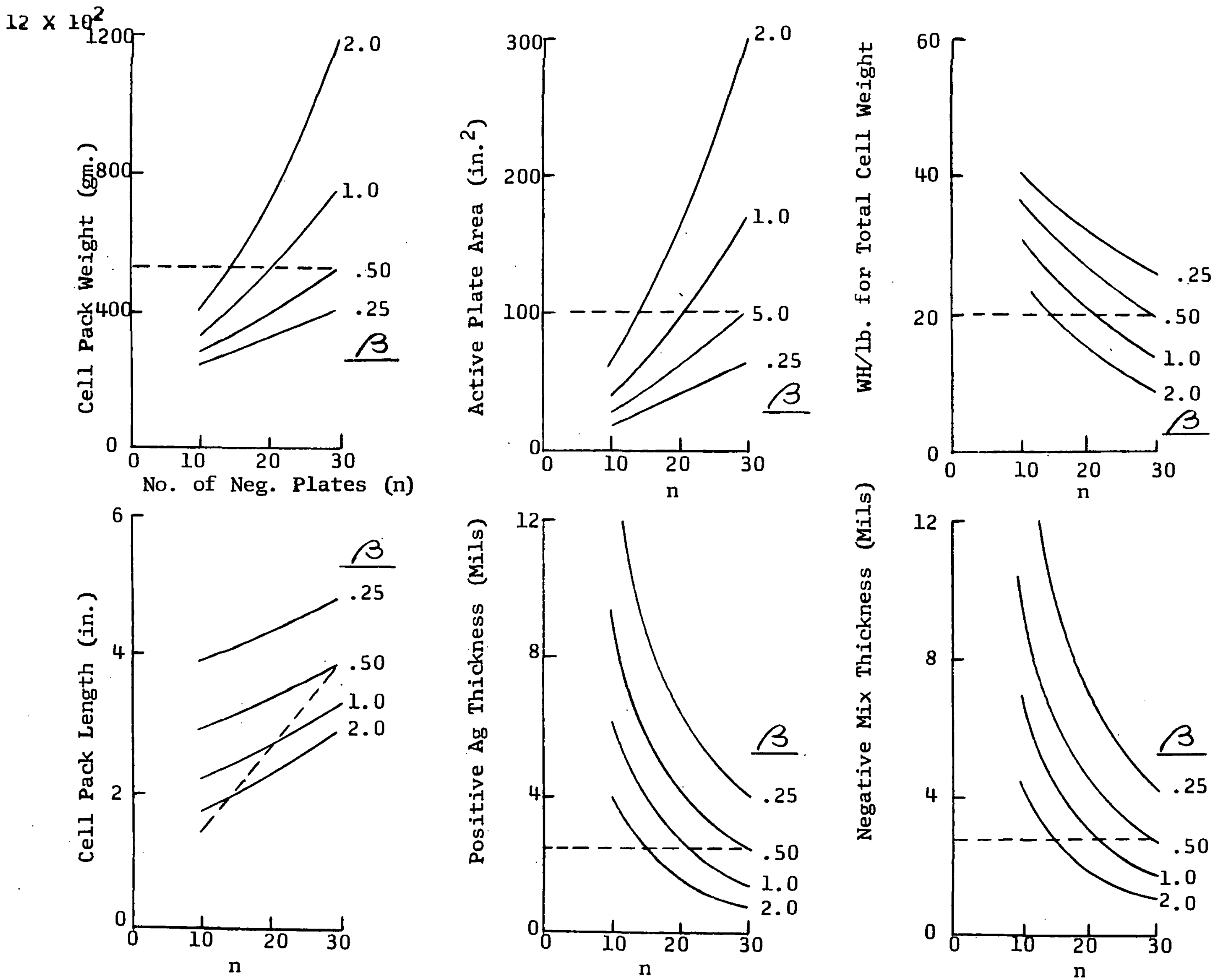


FIGURE 4

POST SHOCK POSITIVE PLATES OF MODEL 362X CELL - S/N 3

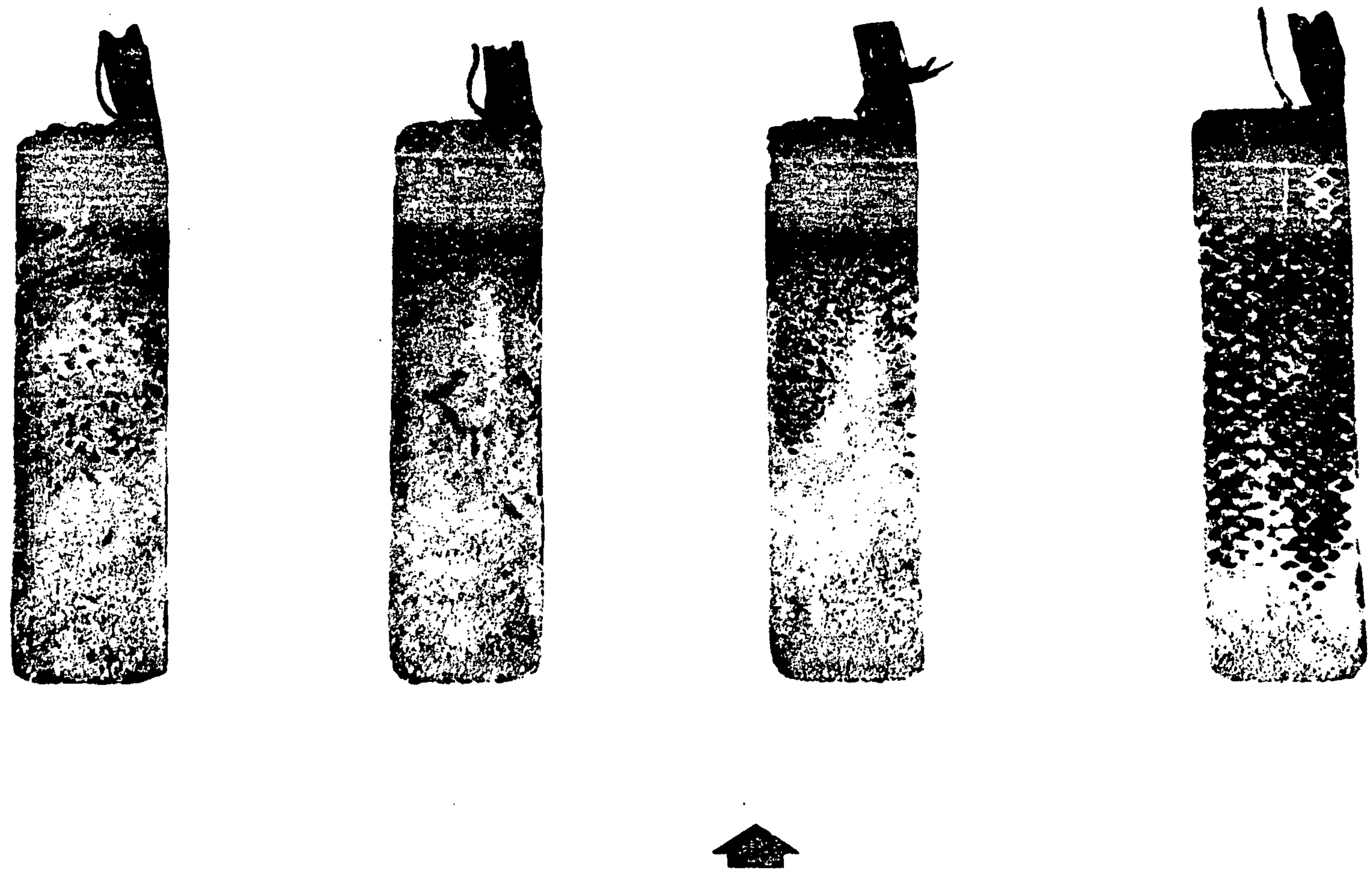
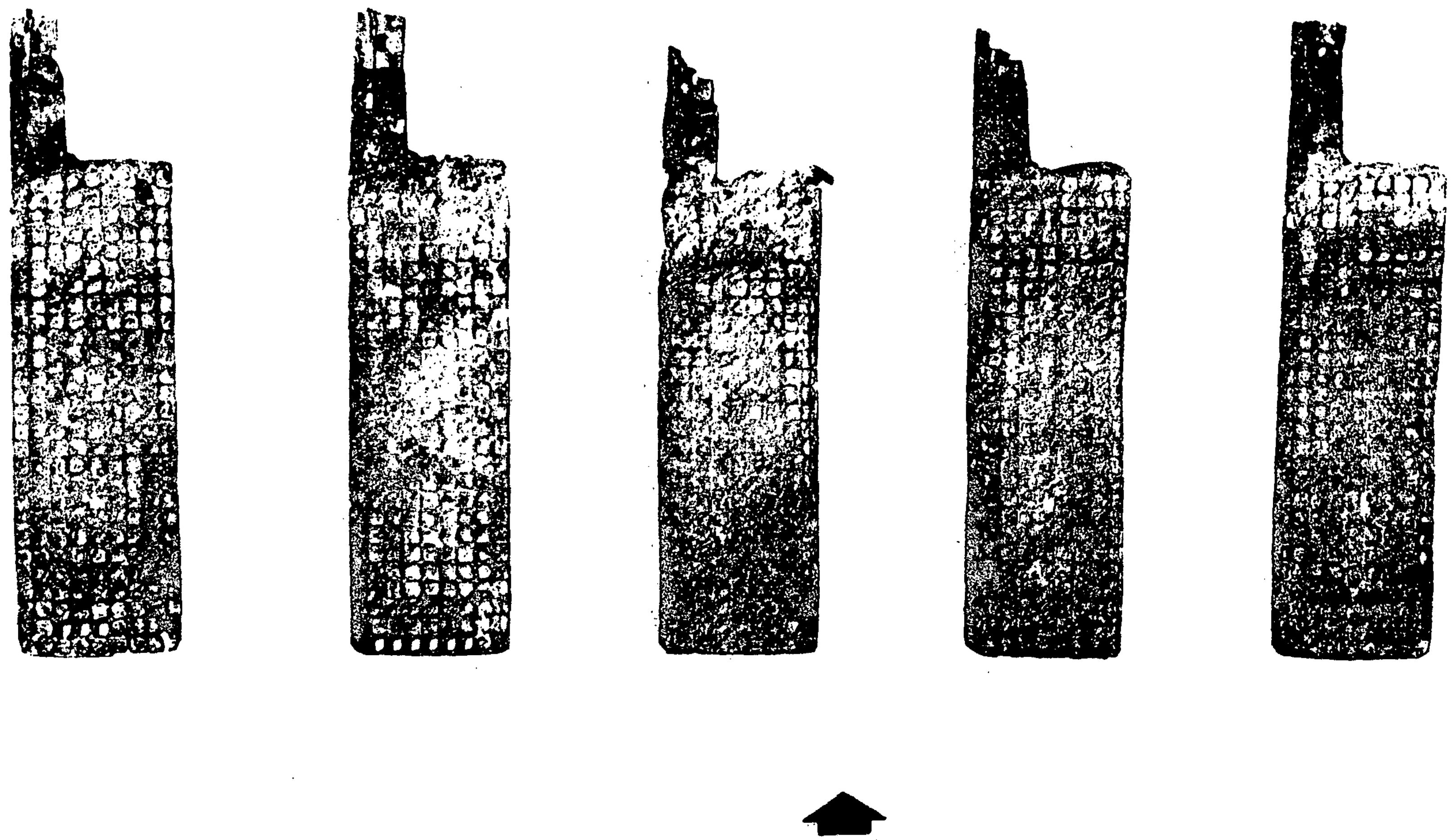


FIGURE 5

POST SHOCK NEGATIVE PLATES OF MODEL 362X CELL - S/N 3



Velocity Vector at 4,000 g's

FIGURE 6

MODEL 362 HIGH IMPACT CELL PLATES

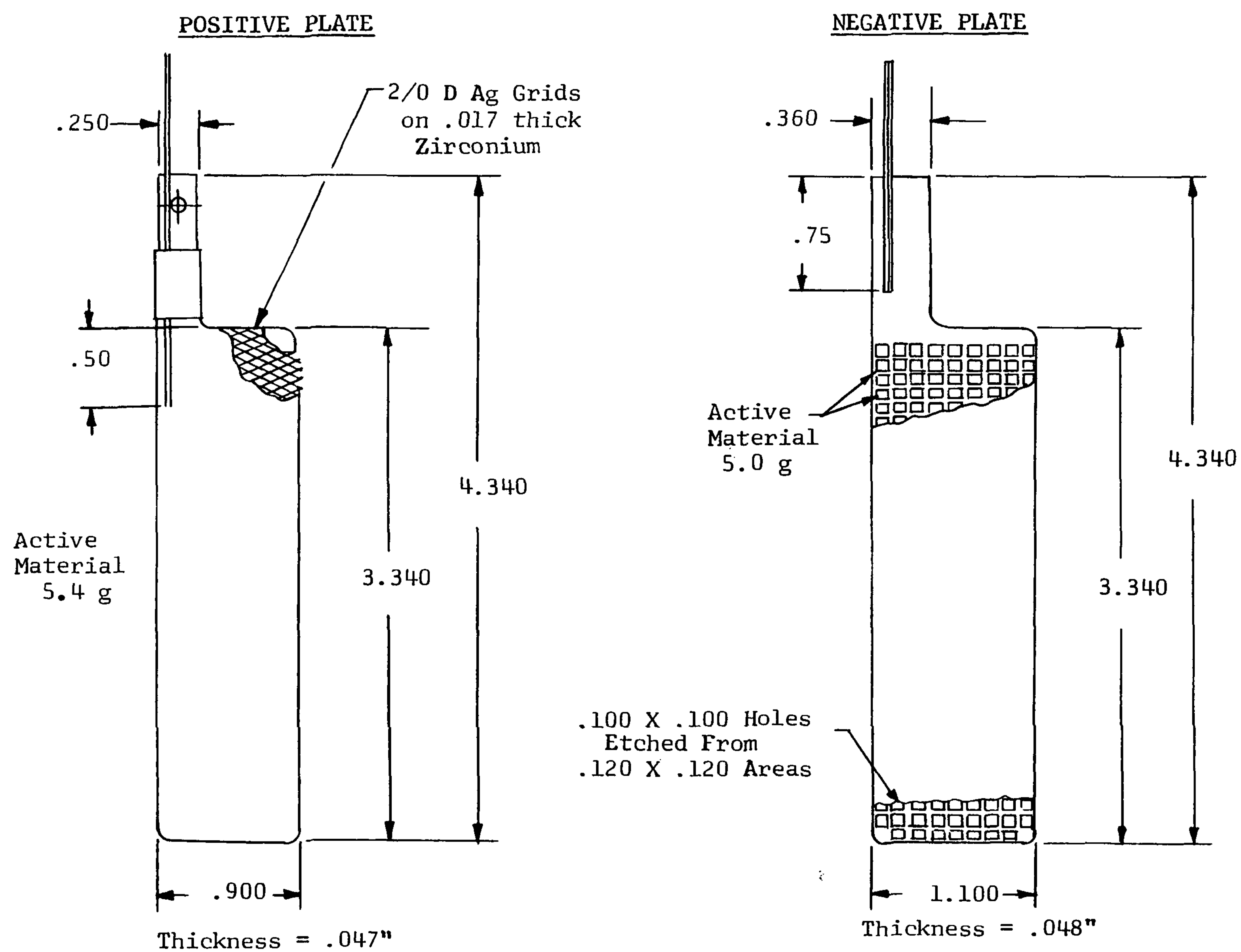


FIGURE 7

MODEL 362 NARROW PLATE, HIGH IMPACT DESIGN

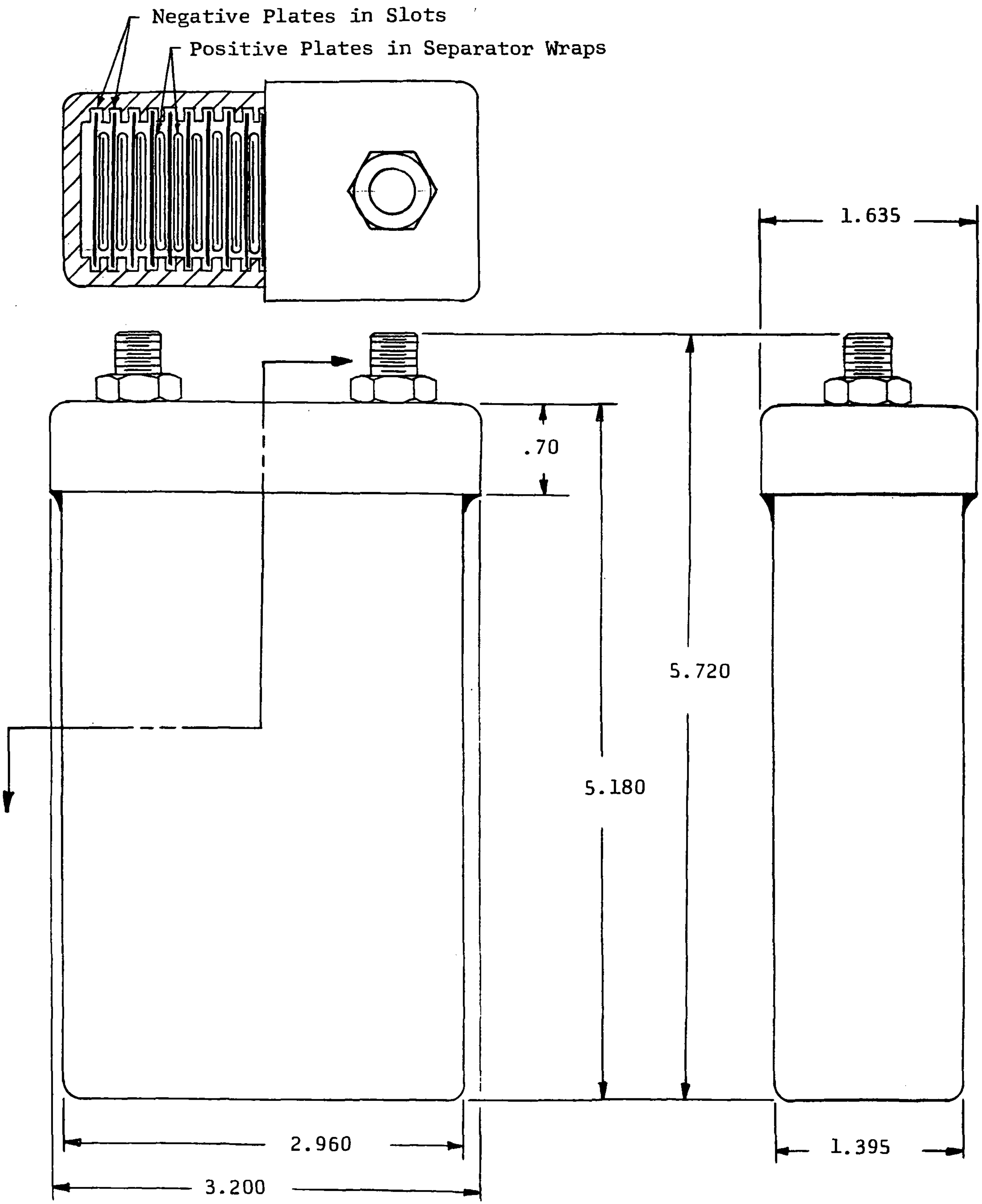


FIGURE 8

MODEL 344, HEAT STERILIZABLE, HIGH IMPACT 5.0 AH CELL

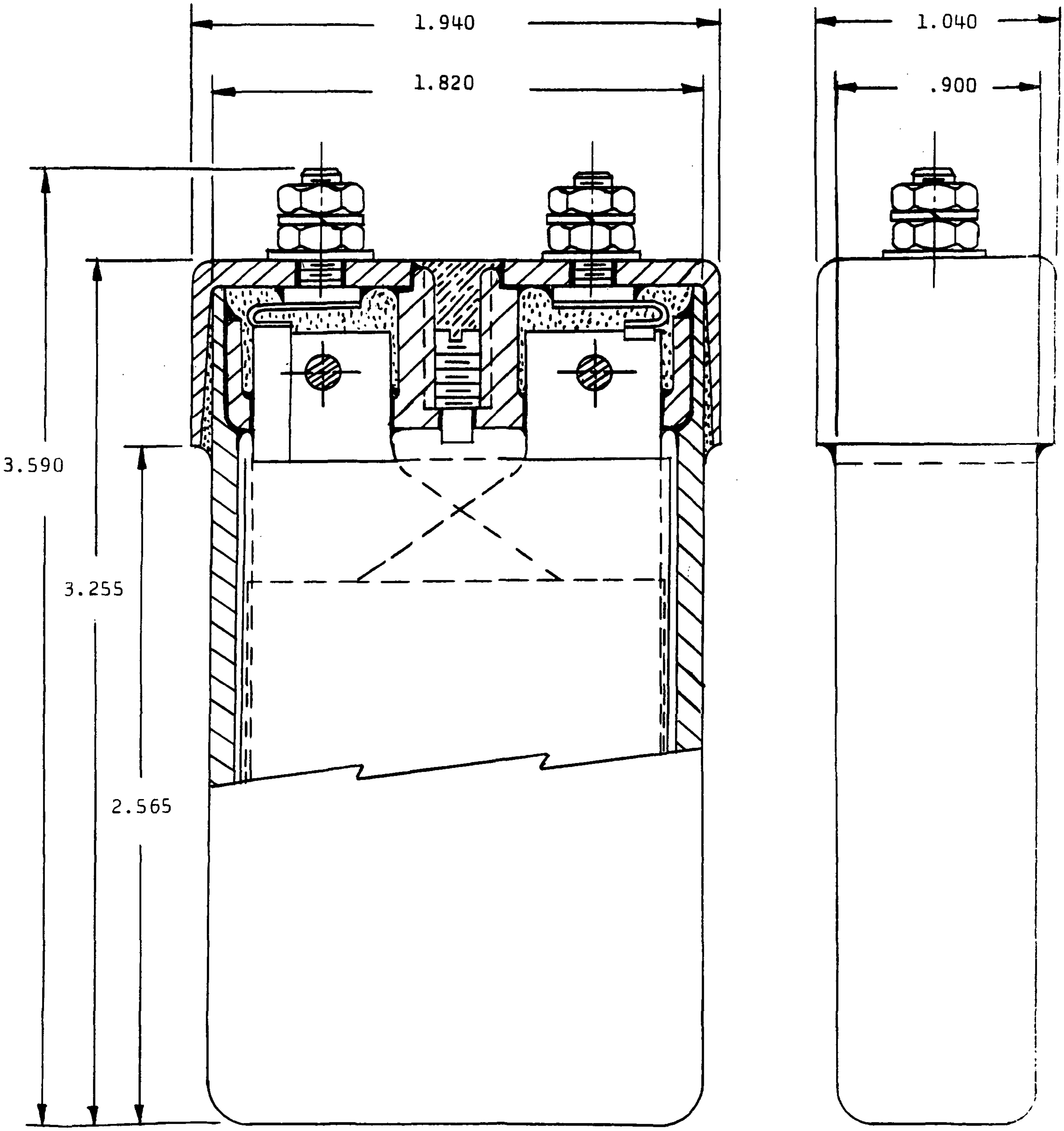
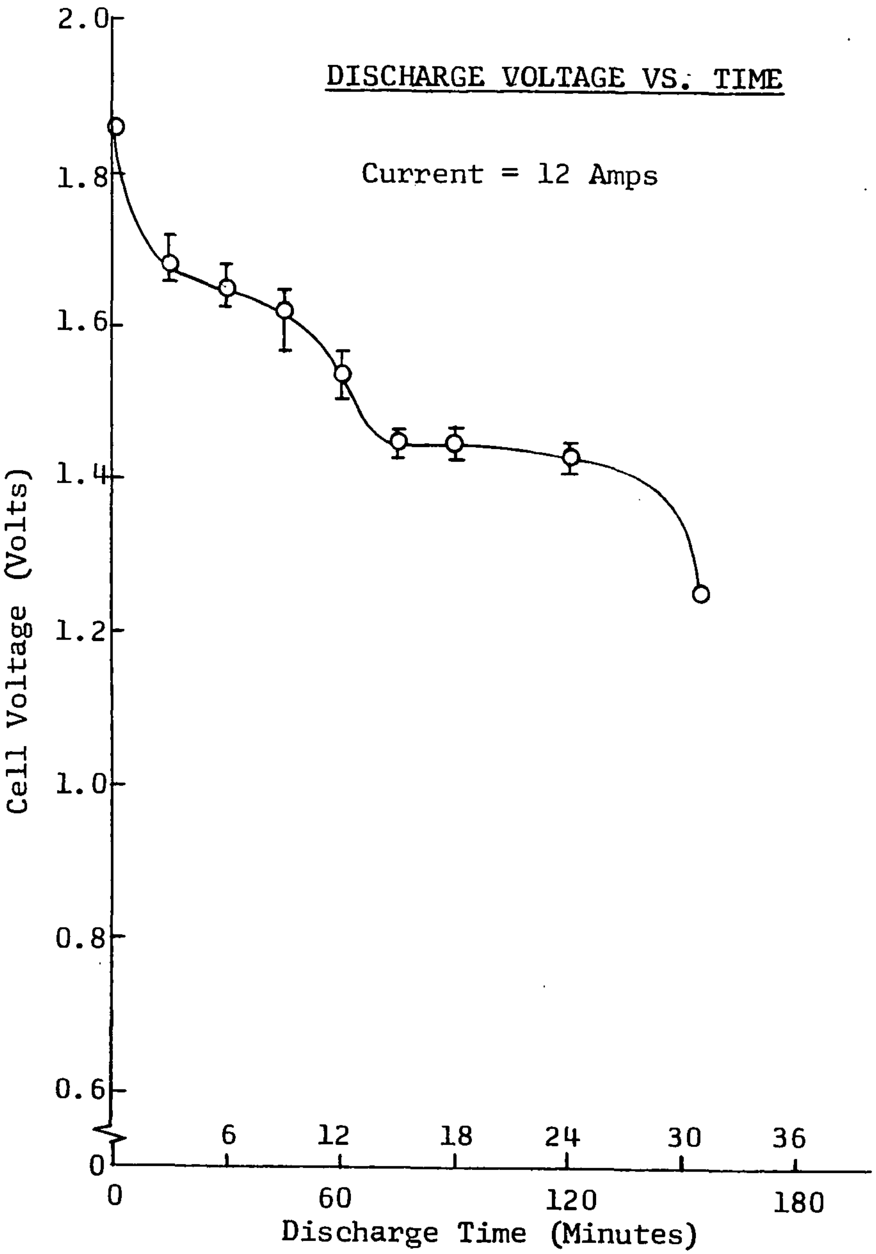


FIGURE 9

ELECTRICAL CHARACTERISTICS OF HIGH IMPACT MODEL 362 CELLS

AVERAGE OF FOUR CELLS - TEMPERATURE = 25°C



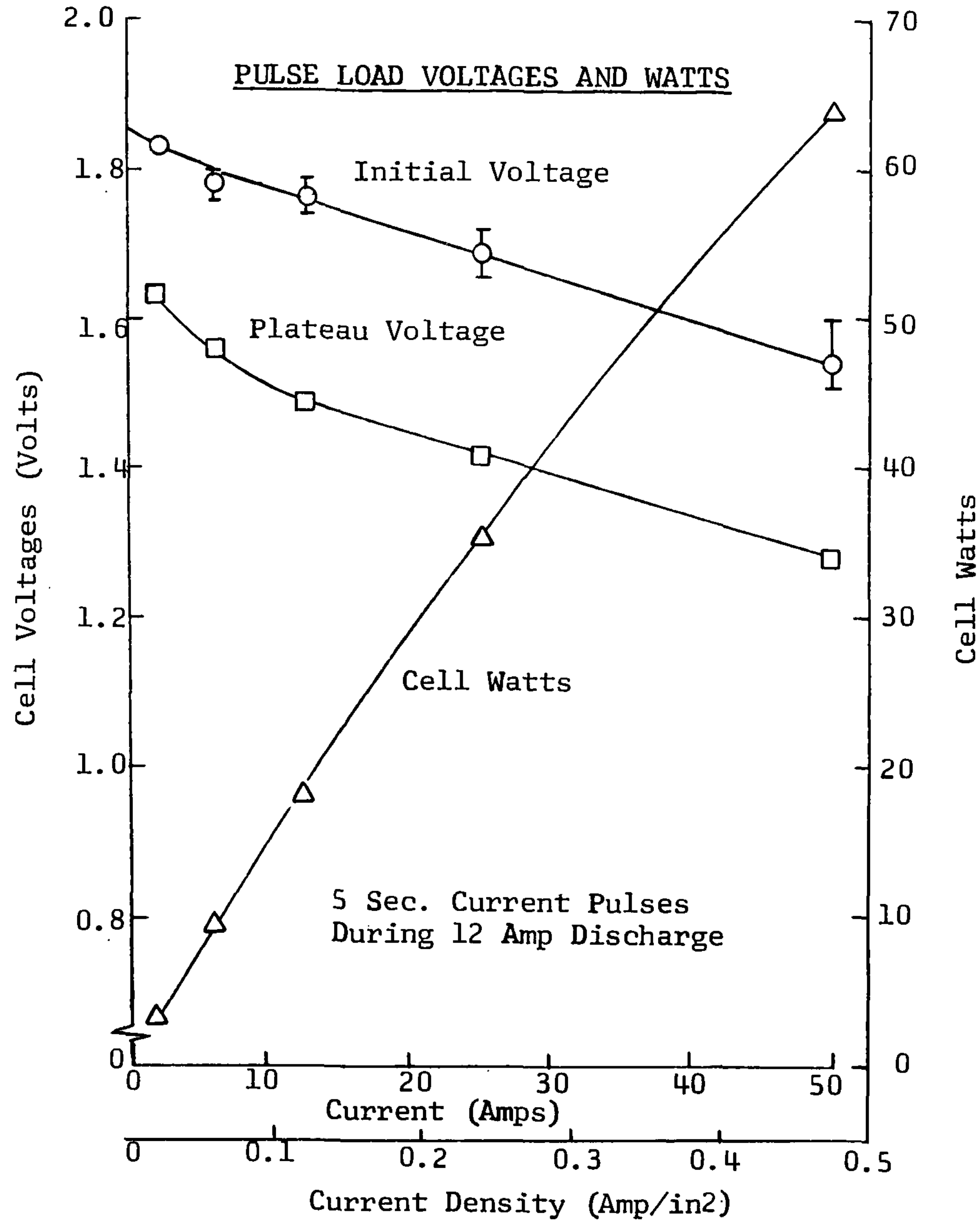


FIGURE 10

CELL VOLTAGES AND REFERENCE VOLTAGES - MODEL 281
CELLS WITH ZIRCONIUM REINFORCED POSITIVES

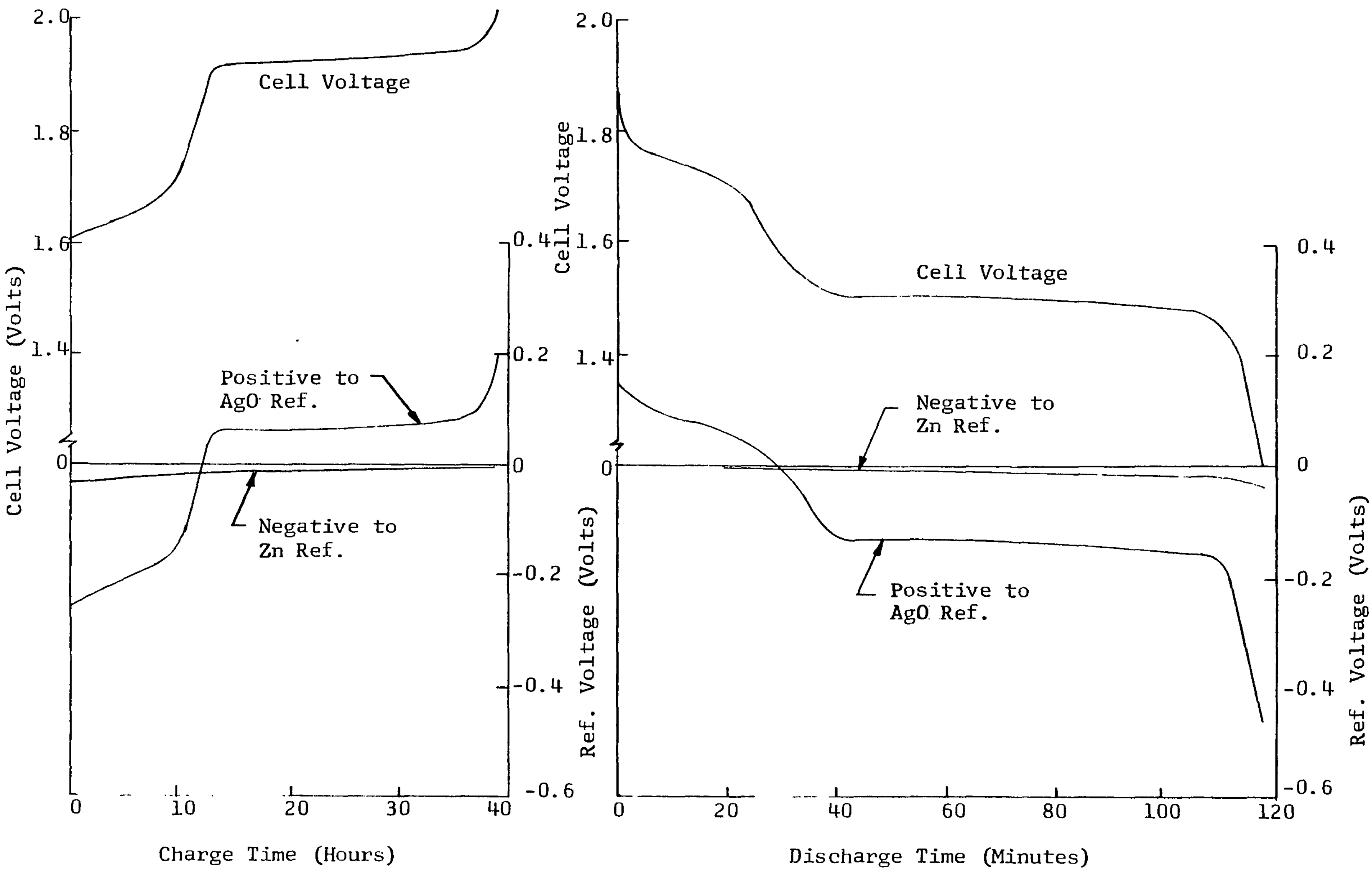


FIGURE 11

MODEL 361, HEAT STERILIZABLE, HIGH IMPACT 5.0 AH CELL

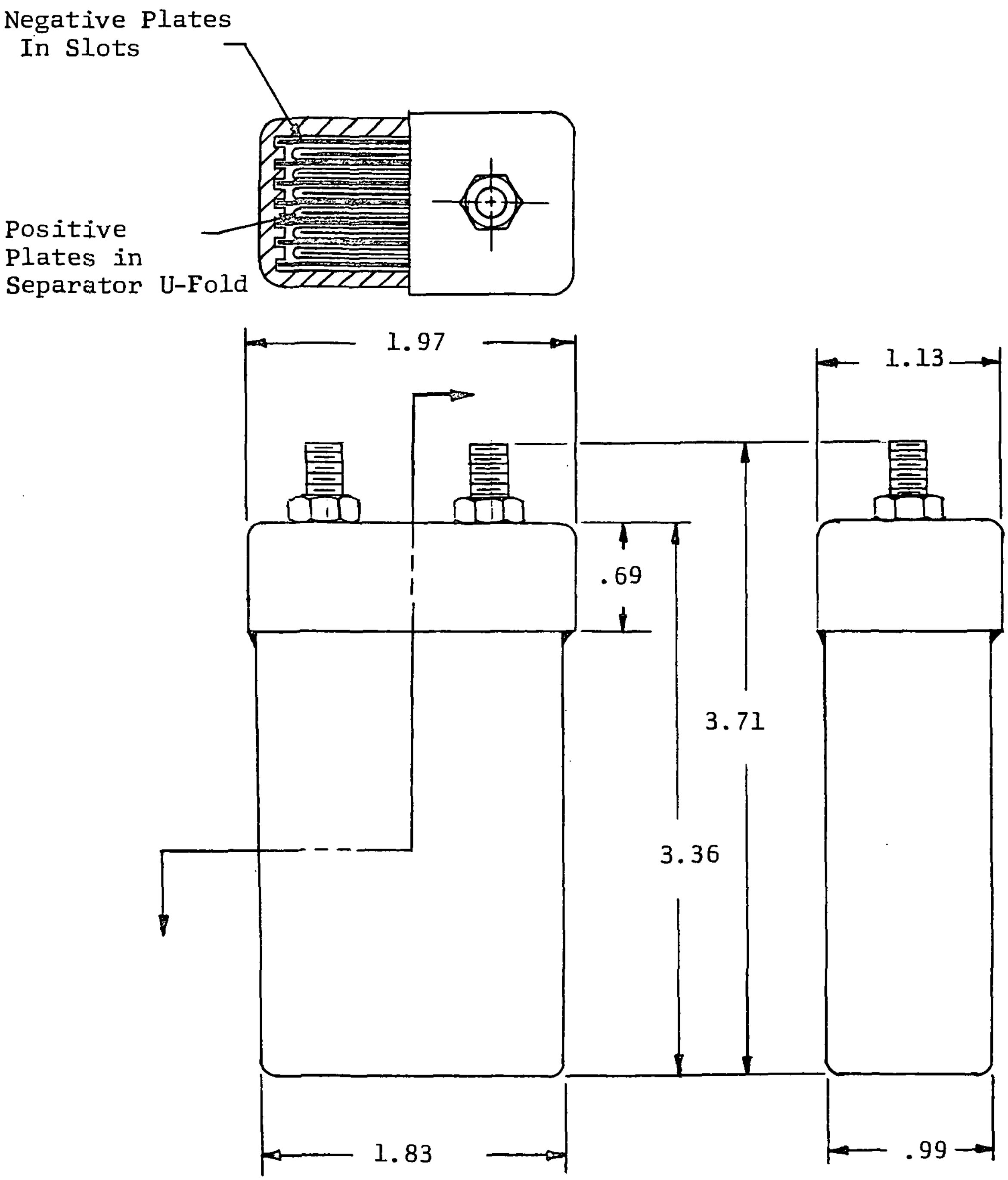


FIGURE 12
VOLTAGE-TIME DISCHARGE CHARACTERISTICS OF
CYCLED 80 AH CELLS BEFORE AND AFTER STERILIZATION

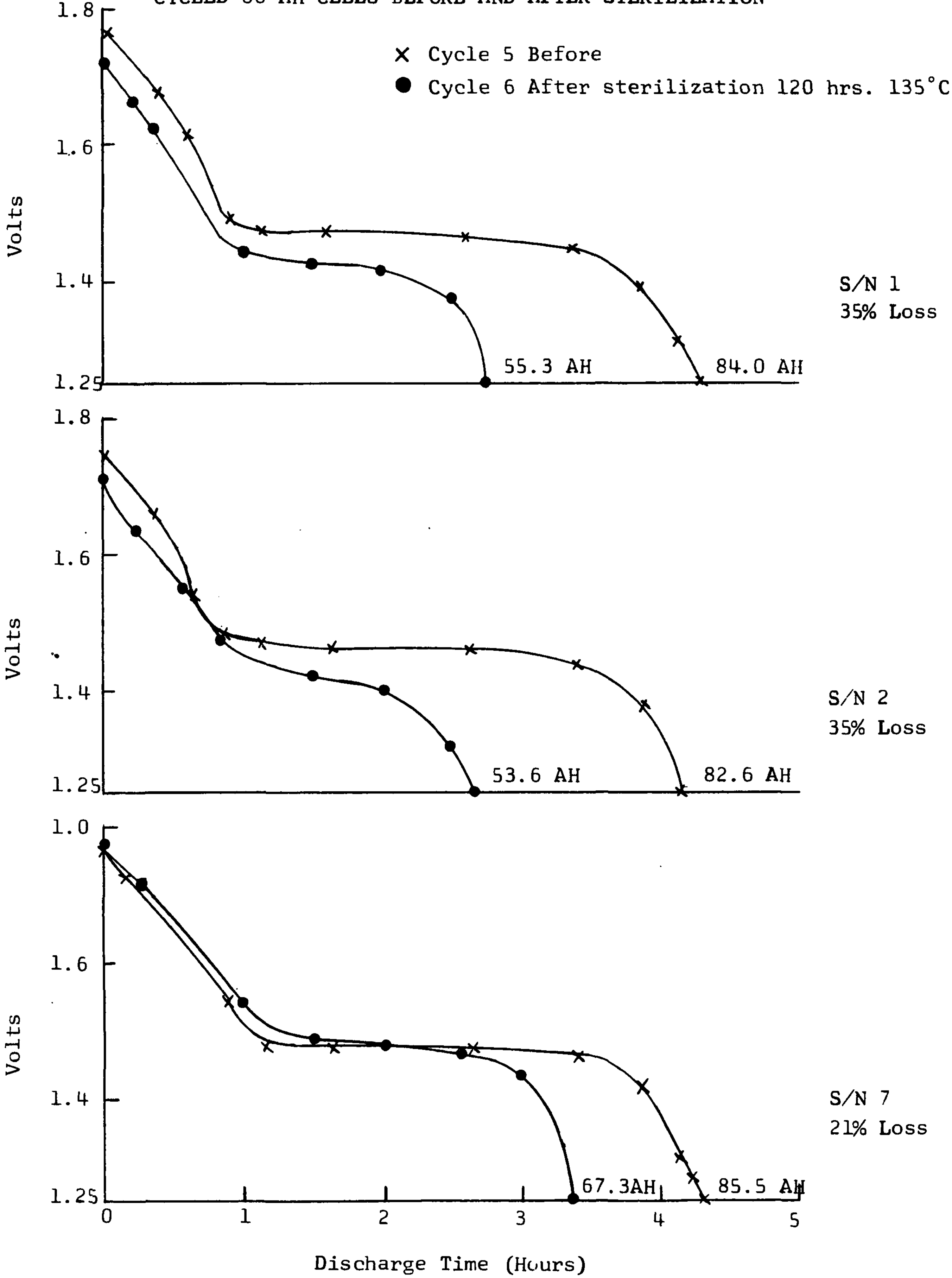


FIGURE 13

TYPICAL DISCHARGE CHARACTERISTICS 70 AH CELLS
ESB MODEL 364

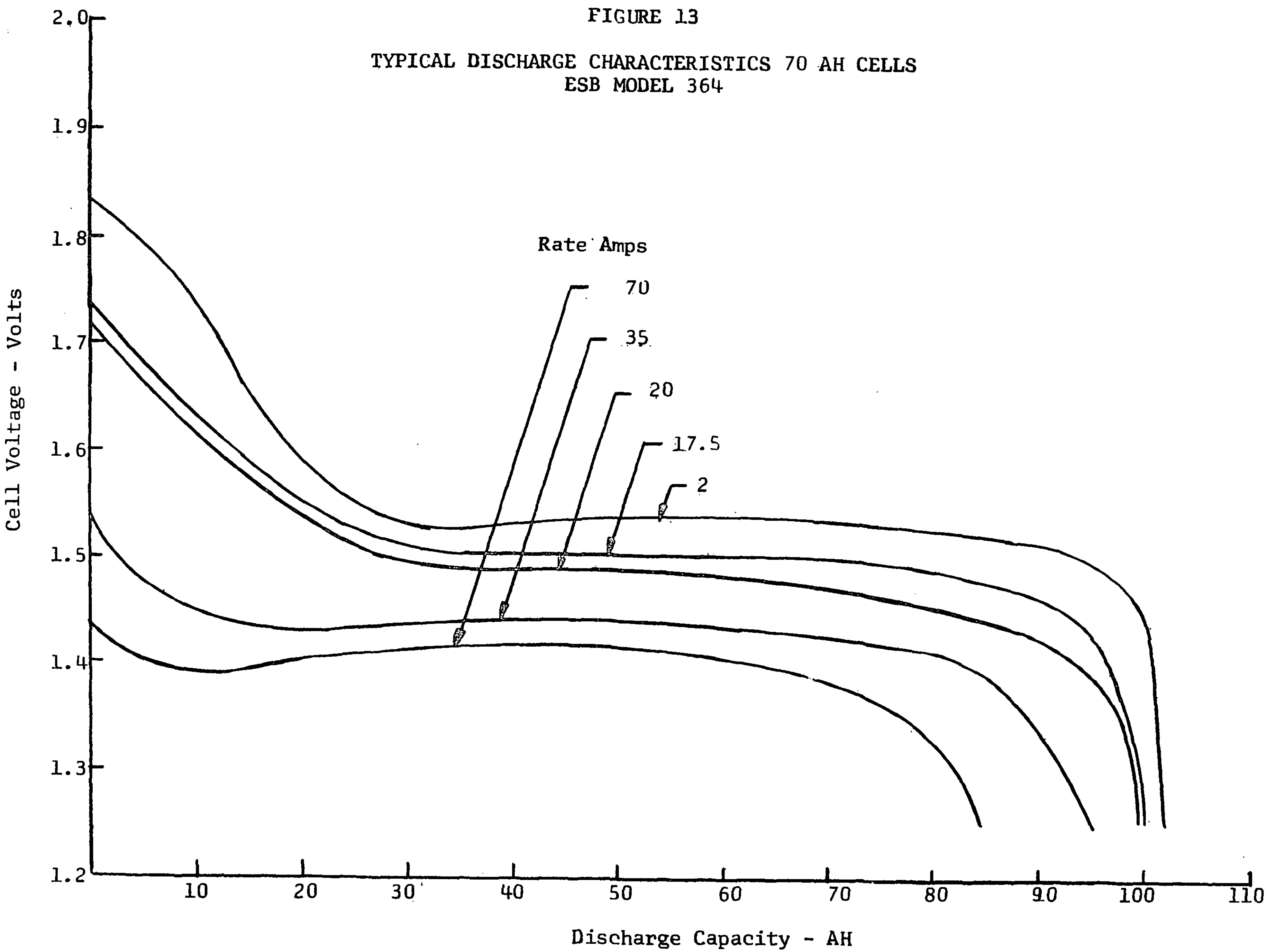


FIGURE 14

DISCHARGE VOLTAGE VS CAPACITY, MODEL 379 NON-HEAT STERILIZED CELLS
8 AMPS TO 1.25 V AT ROOM TEMPERATURE

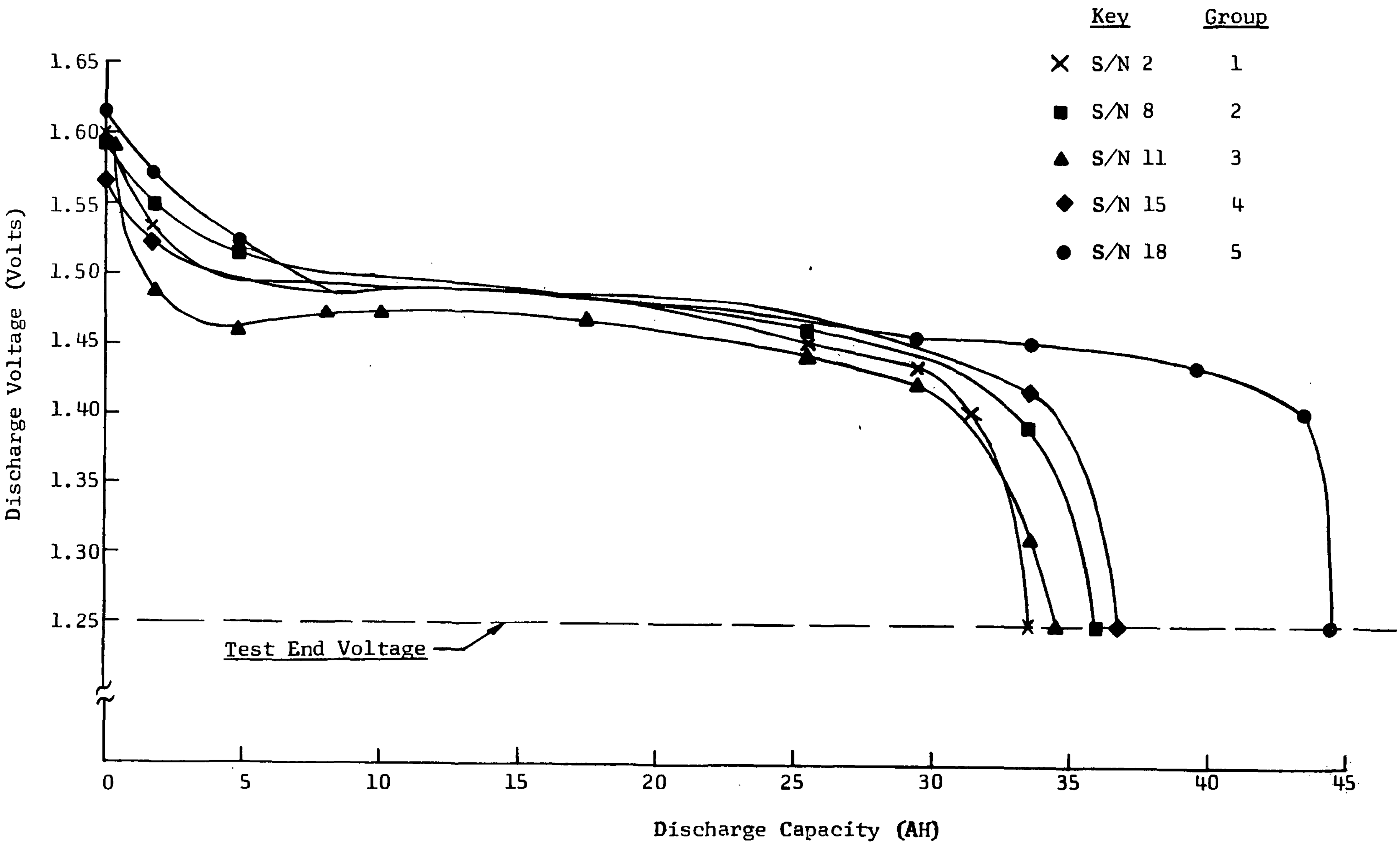


FIGURE 15

EFFECTS OF ABSORBER AND NEGATIVE ADDITIVE ON CAPACITY DURING AUTO-CYCLING OF MODEL 172 (24-AH) CELLS

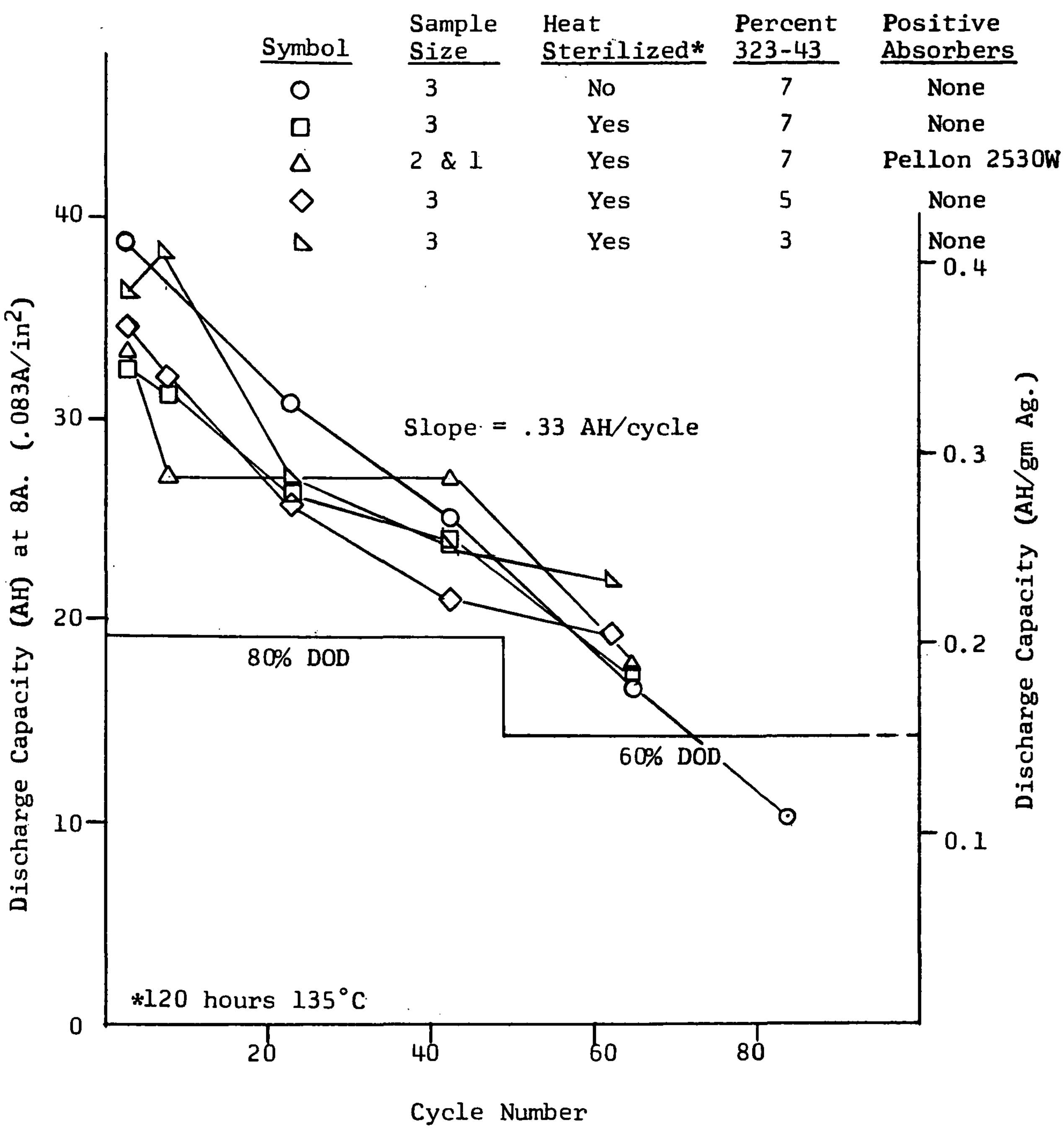


FIGURE 16

MODEL 172 CELL VOLTAGE VS PULSE DISCHARGE

Code	●	○	×	△	▽	□
Mercuric Sulfide, %	7	7	7	5	3	4
Absorber	None	None	Pellon 2530W	None	None	None
Heat Sterilized*	No	Yes	Yes	Yes	Yes	Yes
% Sintered Teflon 7	0	0	0	0	0	5
Cell S/N	1, 2, 3	4, 5, 6	7, 8, 9	10, 11 12	13, 14 15	16, 17

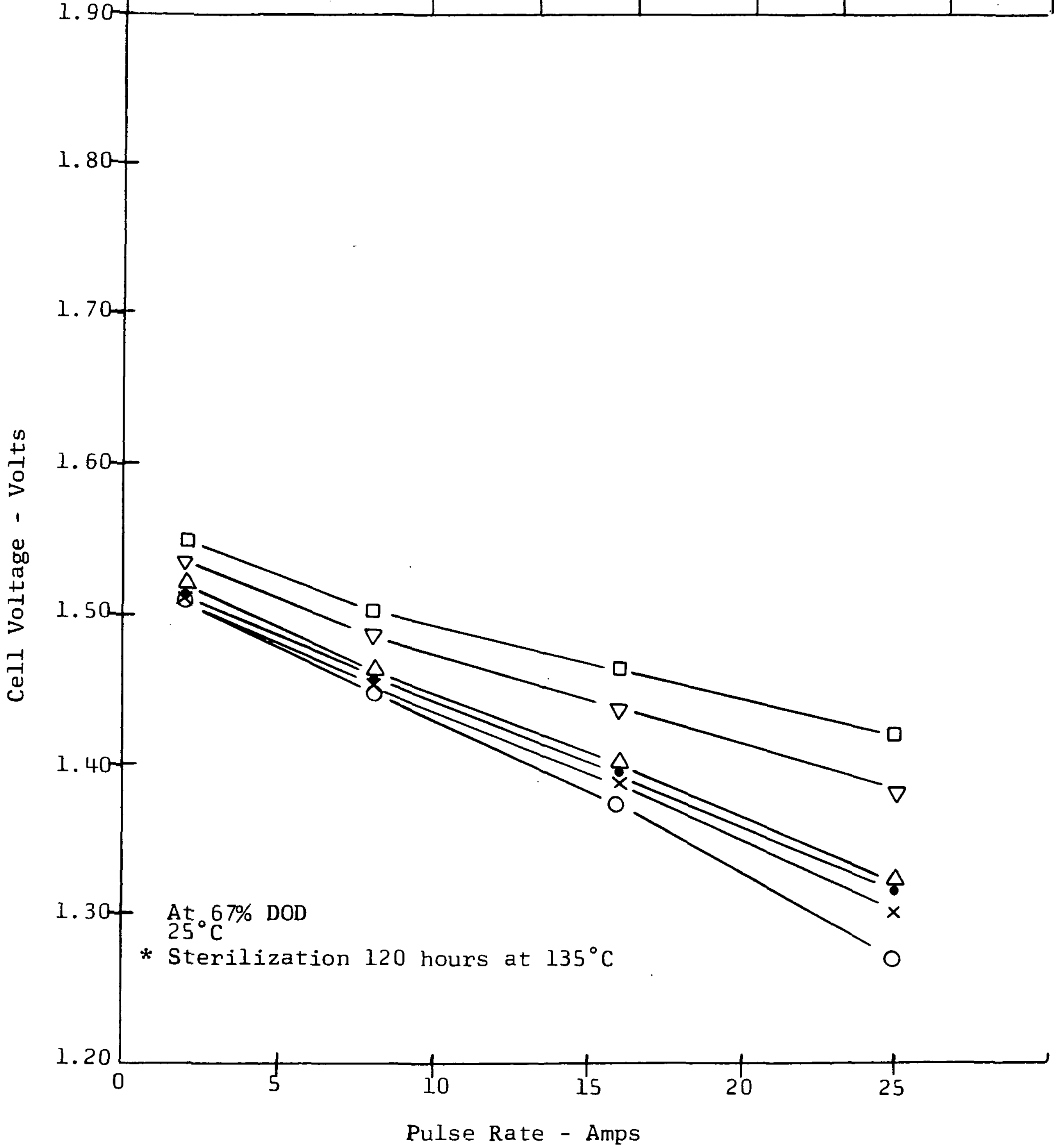


FIGURE 17

MODEL 172 (379) CELL DIMENSIONAL AND CUT-A-WAY VIEW

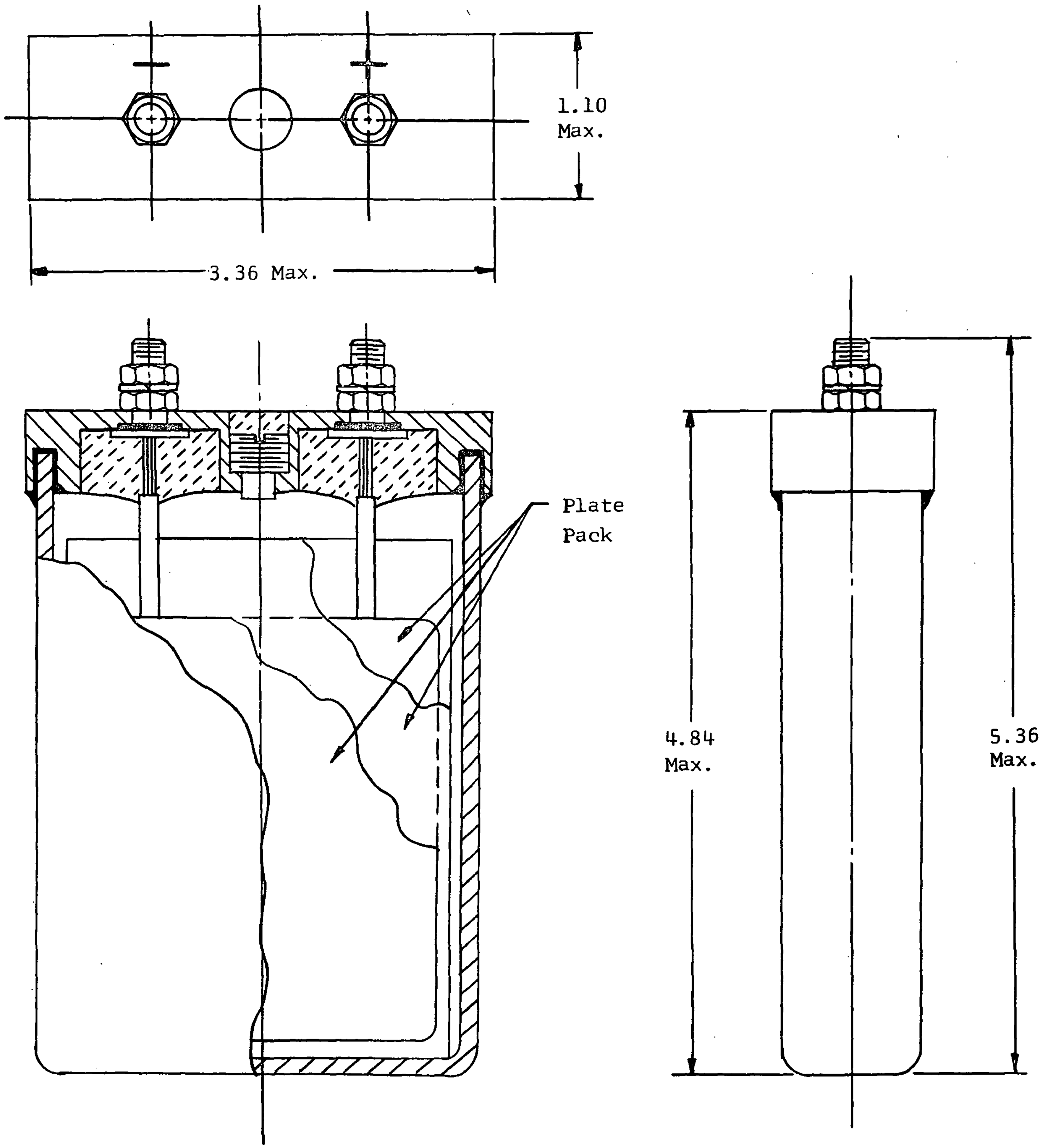


FIGURE 18

EFFECT OF DISCHARGE RATE ON PERFORMANCE
OF 25 AH STERILE, SEALED CELL
(HEAT STERILIZED 120 HOURS AT 125°C)

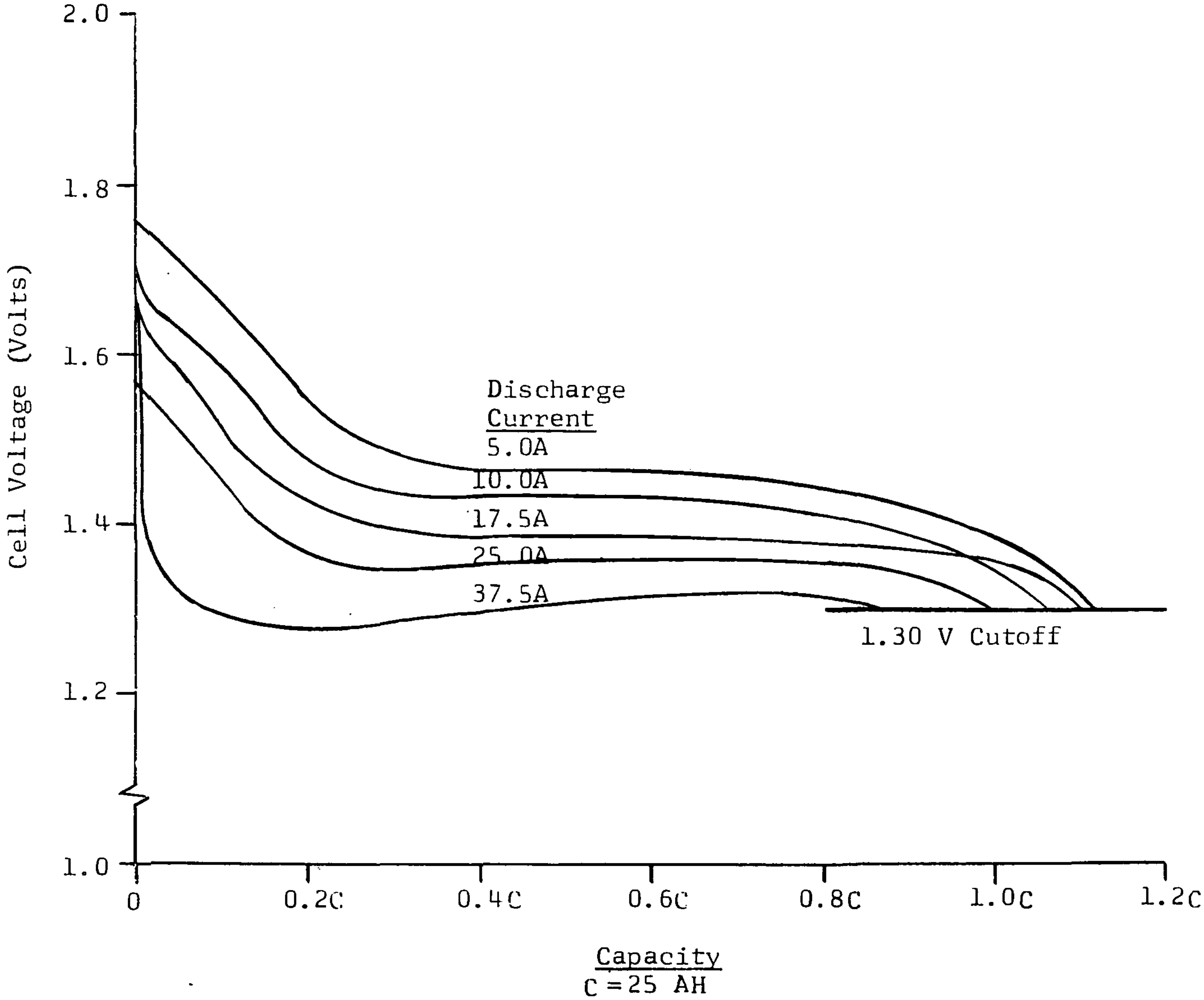


FIGURE 19

CYCLE LIFE, FAILURE MODE, CAPACITY MAINTENANCE

16 AH Cells 100% Depth Cycling

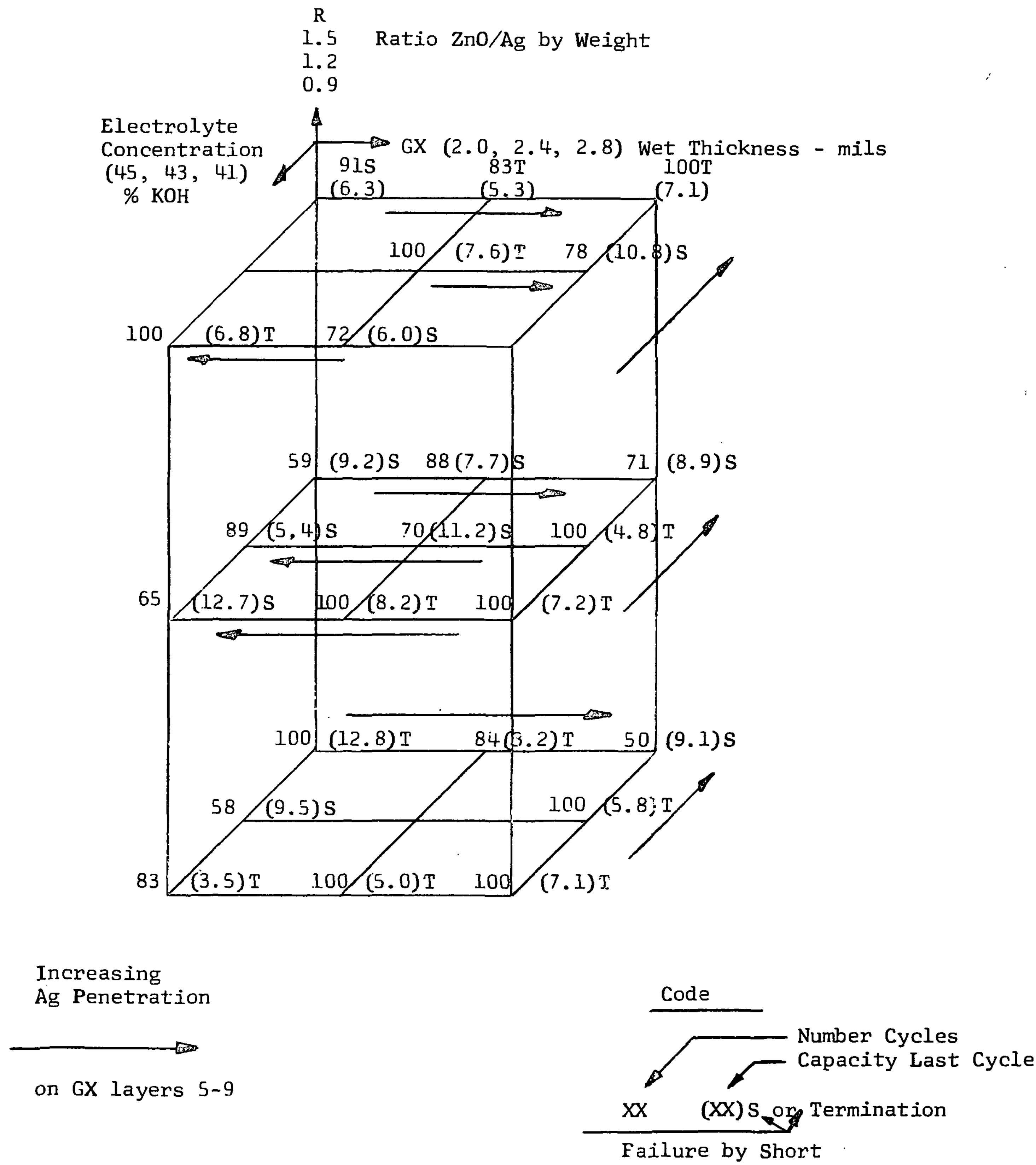


FIGURE 20

END OF DISCHARGE VOLTAGE AND END OF CHARGE CURRENT
DURING 50% DEPTH AUTO-CYCLING

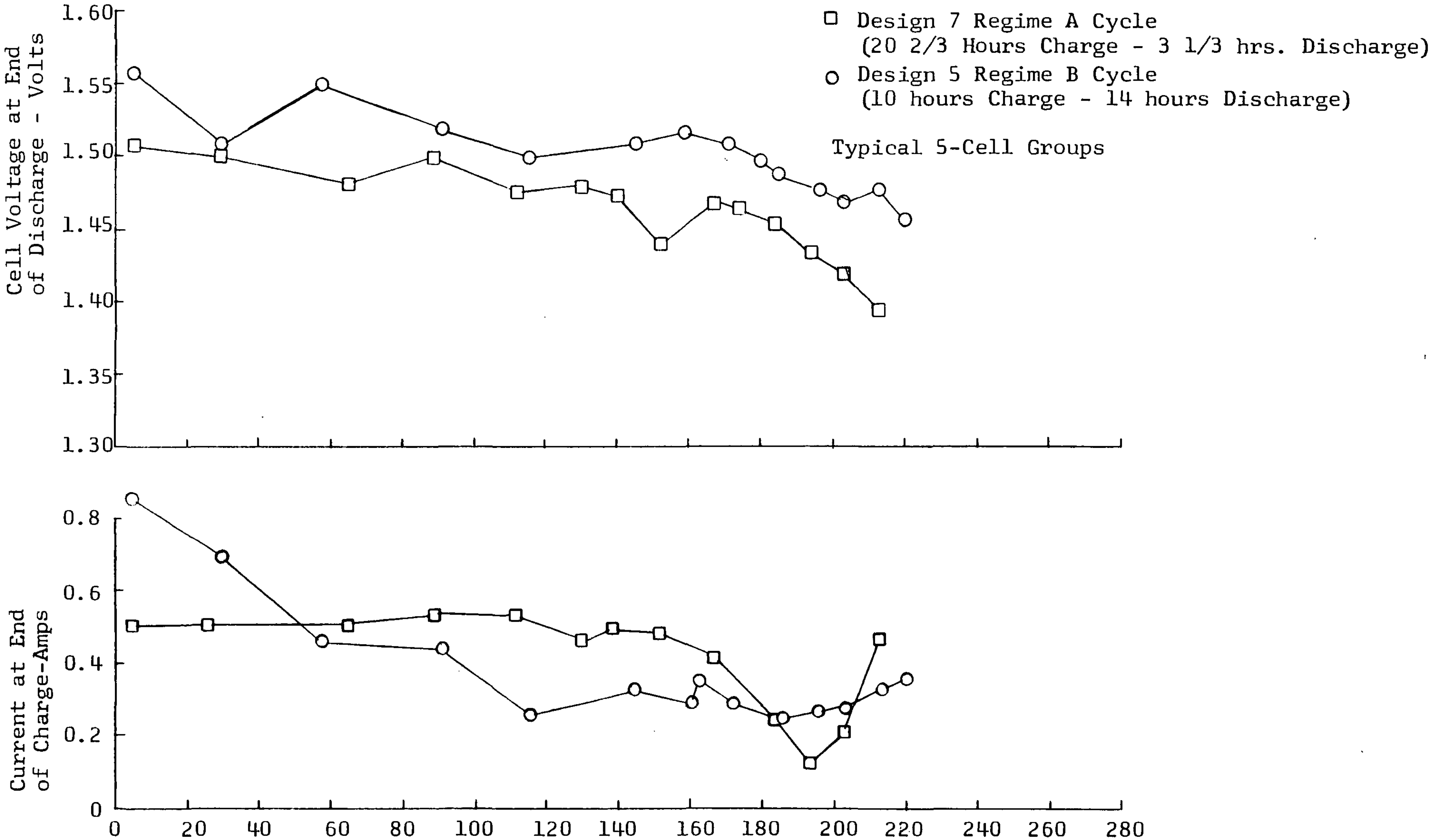


FIGURE 21
MODEL 389 RESIDUAL CAPACITY DURING 50% DEPTH AUTOCYCLING

	Design	Plates Wrapped	Extended Negatives	Negative Shape	Separator System		Design	Plates Wrapped	Extended Negatives	Negative Shape	Separator System
●	1A & 1B	Neg.	No	Flat	10L SWRI-GX 2L EM476I	○	5A & 5B	Pos.	Yes	Flat	10L SWRI-GX 1L Pellon 2140
×	2A & 2B	Pos.	No	Flat	10L SWRI-GX 2L EM476I	⊗	6A & 6B	Pos.	Yes	Flat	10L SWRI-GX 2L EM476I
△	3	Pos.	Yes	Flat	7L SWRI-GX 6L EM476I Spiral Wrap	▽	7A & 7B	Pos.	Yes	Flat	8L SWRI-GX 1L Pellon 2140
□	4	Pos.	Yes	Flat	10L SWRI-GX 2L EM476I	——	A Orbit 20 2/3 Hours Charge, 3 1/3 Hours Discharge				
						— —	B Orbit 10 Hours Charge, 14 Hours Discharge